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Effect of growth rate on wood specific gravity and selected mechanical properties in individual species from distinct wood categories

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Summary This study examined the relationships of wood specific gravity and selected mechanical properties (MOR, MOE and Cmax) with growth rate in 16 timber species from four distinct wood categories: 1) first softwood category (FSC); 2) second softwood category (SSC); 3) diffuse-porous wood category (DPC); and 4) ring-porous wood category (RPC). And genetic, silvicultural and environmental influence on the relationships was briefly discussed. Statistical results show that the relationships of specific gravity and the mechanical properties with growth rate vary remarkably with both the wood property and the wood category. In general, the mechanical properties in the FSC species decrease remarkably with increasing growth rate, while they appear to be less influenced in the SSC species. Compared with the softwoods studied, the physico-mechanical properties in the hardwoods studied are remarkably less influenced. In the DPC species, growth rate generally has very a little influence on both specific gravity and the mechanical properties. In the RPC species, the physico-mechanical properties appear not to decrease with increasing growth rate, and in some species they even tend to increase. Among the three mechanical properties studied, MOE is remarkably less influenced by growth rate than MOR and Cmax. Compared with specific gravity, however, the mechanical properties are generally more influenced by growth rate. Therefore, the impact of growth rate on wood mechanical properties in a species can not be estimated exactly through the relationship of wood specific gravity with growth rate. Path analysis reveals that growth rate has a large effect on the mechanical properties which can be accounted for by the affected specific gravity. In addition to this indirect effect through specific gravity, growth rate still has an additional effect on the mechanical properties which can not be explained by specific gravity. In the SFC species, such effect is significant, and this, to a lesser extent, applies to the DPC species. However, this effect is not remarkable in the SSC species and may be negligible in the RPC species.

Introduction

Fast-growing plantations have steadily increased over the decades worldwide due to the well-known reasons, and the proportion of the plantations of both softwoods and hardwoods will continue to increase until it will predominate in the next quarter-century (Zobel 1980; Bingham 1983). The changing resource throughout the world

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means the changing quality of the world wood supply (Bendtsen 1978; Zobel 1984; Senft et al. 1985; Zobel and van Buijtenen 1989). A better understanding of the changing quality of the wood from fast-grown plantations is helpful to the efficient processing and utilization of the wood.

Although tremendous research has been done on the relationship of wood specific gravity with growth rate over the decades (cf. Panshin and de Zeeuw 1980; Zobel and van Buijtenen 1989; Zhang and Zhong 1991), much fewer studies (Olson et al. 1947; Cheng et al. 1960; Cheng 1962, 1963; Pearson and Gilmore 1980; Pearson and Ross 1984; Smith 1990; Leban et al. 1992) have explored the influence of growth rate on wood mechanical properties. As far as the relationship of specific gravity with growth rate is concerned, various controversial results have been reported (cf. Spurr and Hsuing 1954; Larson 1972; Zobel and van Buijtenen 1989; Zhang and Zhong 1991), and the relationship appears to be quite complicated. Furthermore, most studies covered only a single species, and most species studied so far are restricted to some economically important softwoods. Very few studies have compared different species or groups in terms of their changes in wood quality with growth rate. As a result, a general relationship between wood quality and growth rate in individual species is still very ambiguous. Just as Zobel and van Buijtenen (1989) described, there still is much controversy despite the very widespread interest and study over the years, and a research of the literature will yield publications which can support nearly any chosen point of view. The effect of growth rate on wood quality, however, has enough potential importance that it must always be considered and cannot be ignored for any species.

An attempt was therefore made in this study: 1) to evaluate the influence of growth rate on both specific gravity and mechanical properties so that we can explore whether the relationship of wood specific gravity with growth rate in a species is useful for estimating the impact of growth rate on wood mechanical properties; 2) to examine the relationship between growth rate and wood properties in different species from distinct wood categories so that we can explore whether appreciable difference in the relationship exists between individual species from distinct wood categories. Finally, we also attempted to explore how growth rate affects wood mechanical properties, and this effect, to which extent, can be accounted for by the affected wood specific gravity.

Materials and methods

In total, 16 economically important species were examined in this study. These species were selected from 8 common genera which fall into the following 4 distinct wood categories defined by Zhang (1994a):

1) First softwood category (FSC): softwoods with gradual transition from earlywood to latewood;
2) Second softwood category (SSC): softwoods with abrupt transition from earlywood to latewood;
3) Ring-porous wood category (RPC);
4) Diffuse-porous wood category (DPC).

Two fir species (*Abies fabri* and *Abies nephrolepis*) and two spruce species (*Picea asperata* and *Picea koraiensis*) were selected from the FSC, two larch species (*Larix gmelini* and *Larix olgensis*) and two hard pine species (*Pinus massoniana* and *Pinus yunnanensis*) from the SSC, two birch species (*Betula platyphylla* and *Betula utilis*) and two poplar species (*Populus cathayana* and *Populus tomentosa*) from the DPC, and two evergreen chinkapin species (*Castanopsis carlesii* and *Castanopsis fargesii*) and two oak species (*Quercus aliena* and *Quercus mongolica*) from the RPC. At least 5 (up to 10) sample trees were selected from the same locality according to the standard procedures

(NSB 1980) to represent each species studied. From the breast height of the trees selected, at least 30 small clear specimens (except *Betula platyphylla*) were prepared for testing each mechanical property. This study focused on the following three major mechanical properties: 1) modulus of rupture in static bending (MOR); 2) modulus of elasticity in static bending (MOE); and 3) maximum crushing strength in compression parallel to the grain (Cmax). The specimens were prepared and tested according to the Chinese National Standard (NSB 1980). The specimens for the bending tests are 2 cm (radial) by 2 cm (tangential) by 30 cm (longitudinal), and the specimens for the compression tests are 2 cm (radial) by 2 cm (tangential) by 2 cm (longitudinal). The three mechanical properties studied were adjusted to the values at air-dry condition. Wood specific gravity of each specimen was measured on the basis of ovendry weight/air-dry volume. Average ring width of each specimen was measured to 0.01 mm. For further information on the sampling and testing methods, refer to Zhang (1994a) and NSB (1980).

Ring width in this study, as in many studies (cf. Zobel and van Buijtenen 1989), serves as a relative measure of the radial growth rate. The influence of the growth rate on wood specific gravity and mechanical properties studied was examined in each species by correlation analysis and regression analysis, and the difference in the influence between different species was then considered in the light of the distinct wood categories recognized. Moreover, path analysis (cf. Zhang 1986, 1992; Zhang et al. 1992) was used to explore the relationships of interrelated growth rate and wood specific gravity with the three mechanical properties in individual species.

Results and discussion

Table 1 lists the mean and coefficient of variation for growth rate, wood specific gravity and the three mechanical properties in the 16 softwoods and hardwoods. The softwoods studied as a whole have a lower specific gravity than the hardwoods. This applies to the mechanical properties as well. However, no consistent difference in growth rate can be recognized between the softwoods and the hardwoods. The softwoods show a larger variation in both specific gravity and the mechanical properties than the hardwoods, as indicated by the coefficient of variation. However, no remarkable difference in growth rate exists between the softwoods and the hardwoods. Among various variables studied, growth rate shows the largest variation (from 26.9% to 52.3%), followed by the wood mechanical properties (from 6.0% to 19.7%), while wood specific gravity has the least variation (from 4.6% to 12.1%).

Influence of growth rate on specific gravity and the mechanical properties in individual species from distinct wood categories

As shown in Fig. 1, specific gravity in *Abies nephrolepis* decreases gradually with increasing growth rate. A negative correlation coefficient (−0.24) was thus found in this species between wood specific gravity and growth rate (Table 2). But the negative correlation is not significant statistically. A highly significant negative correlation was found in this species between the three mechanical properties (MOR, MOE and Cmax) and growth rate (−0.59, −0.41 and −0.46, respectively). With increasing growth rate the mechanical properties in the species decrease obviously more remarkably than specific gravity (see Fig. 2 for MOR as an example). A similar case was noticed in other FSC species (except *Picea koraiensis*, see Table 2). This statistical result indicates that the physico-mechanical properties in the FSC species decrease remarkably with increasing growth rate. The result further reveals that growth rate in the FSC species have a larger effect on the mechanical properties than on specific gravity. Therefore, the impact of growth rate on wood mechanical properties in a species may not be exactly

Table 1. Mean and coefficient of variation (C.V.) of growth rate (GR, in mm), specific gravity (SG), and three mechanical properties (MOR, MOE and Cmax, all in MPa) in individual species from 4 distinct wood categories

Category	Species	GR Mean / C.V. (%)	SG Mean / C.V. (%)	MOR Mean / C.V. (%)	MOE Mean / C.V. (%)	Cmax Mean / C.V. (%)
FSC	*Abies nephrolepis*	2.12	0.395	64.6	9398	36.7
		37.4	9.2	9.5	10.6	8.7
	Abies fabri	1.55	0.444	72.9	9950	39.7
		49.4	12.1	13.6	19.7	12.7
	Picea asperata	2.63	0.358	52.9	5258	26.5
		37.0	8.0	11.9	17.2	12.1
	Picea koraiensis	2.73	0.449	77.0	12361	39.4
		36.0	8.8	14.3	15.1	11.2
SSC	*Larix gmelini*	1.37	0.661	112.4	13870	59.8
		28.2	9.7	12.8	16.1	9.4
	Larix olgensis	1.18	0.592	94.1	11662	52.0
		26.5	9.9	10.1	13.7	8.3
	Pinus massoniana	4.56	0.468	76.5	11718	38.6
		42.1	12.4	19.0	25.5	18.3
	Pinus yunnanensis	2.92	0.606	100.8	13812	47.6
		35.3	11.2	14.7	16.5	16.5
DPC	*Betula platyphylla*	1.87	0.609	90.9	9247	41.8
		38.5	7.6	7.2	10.4	9.8
	Betula utilis	1.81	0.617	102.4	9552	44.4
		28.6	4.6	5.9	9.5	9.7
	Populus cathayana	5.66	0.451	65.6	8095	37.4
		46.9	6.6	9.4	7.7	8.0
	Populus tomentosa	5.38	0.536	77.7	10414	43.0
		34.6	6.5	7.9	12.4	7.6
RPC	*Castanopsis carlessi*	4.07	0.539	78.5	9849	38.7
		31.7	9.1	12.2	6.0	8.0
	Castanopsis fargesii	3.30	0.877	138.7	15683	64.3
		26.9	6.4	10.5	13.2	12.5
	Quercus aliena	1.98	0.871	127.7	15791	67.9
		52.3	10.8	17.0	18.5	19.2
	Quercus mongolica	1.58	0.764	122.2	15079	55.3
		30.4	5.1	9.5	11.1	7.5

estimated through the relationship of specific gravity with growth rate. In the two hard pines from the second softwood category, both specific gravity and the mechanical properties (except MOE) are significantly and negatively correlated with growth rate. In the two *Larix* species from the same wood category, however, both specific gravity and the mechanical properties are not significantly correlated with growth rate. As a whole, therefore, growth rate appears to have less influence on the SSC species than on the FSC species. The statistical results on the SSC species indicate that the influence of growth rate on the mechanical properties in these species, unlike in the FSC species, is generally comparable with the influence on specific gravity. Among the three mechanical properties studied, MOE is remarkably less influenced by growth rate in the two hard pines (Table 2). This, to a lesser extent, appears to be true in several other

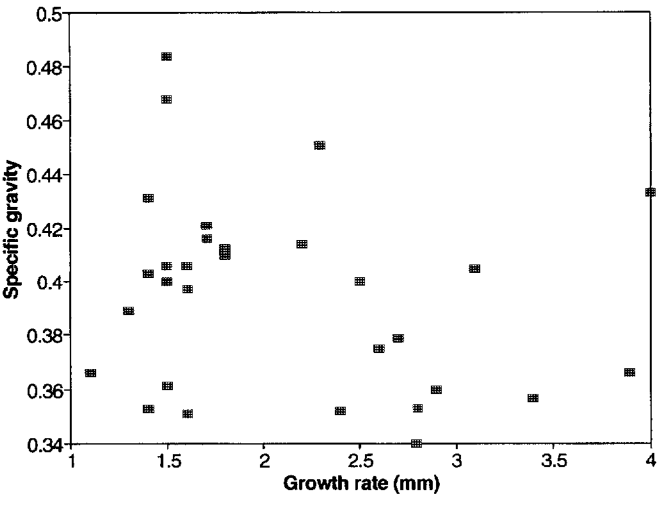

Fig. 1. Specific gravity in relation to growth rate in *Abies nephrolepis*

Table 2. Correlation coefficients of growth rate with specific gravity (SG) and three mechanical properties in individual species from 4 distinct wood categories

Category	Species	SG	MOR	MOE	Cmax
FSC	*Abies nephrolepis*	−0.24	−0.59**	−0.41*	−0.46**
	Abies fabri	−0.34	−0.52**	−0.53**	−0.49**
	Picea asperata	−0.20	−0.58**	−0.49**	−0.71**
	Picea koraiensis	−0.74**	−0.69**	−0.72**	−0.77**
SSC	*Larix gmelini*	−0.14	−0.35	−0.37	−0.32
	Larix olgensis	−0.24	−0.22	+0.16	−0.21
	Pinus massoniana	−0.70**	−0.60**	−0.30	−0.66**
	Pinus yunnanensis	−0.72**	−0.75**	−0.69	−0.73**
DPC	*Betula platyphylla*	−0.34	−0.42	−0.40	−0.43
	Betula utilis	+0.06	−0.21	−0.40	−0.33
	Populus cathayana	−0.06	−0.01	−0.05	+0.03
	Populus tomentosa	−0.11	−0.08	+0.08	+0.42*
RPC	*Castanopsis carlessi*	+0.07	+0.16	−0.14	−0.07
	Castanopsis fargesii	−0.10	−0.10	−0.17	−0.05
	Quercus aliena	+0.28	+0.39*	+0.28	+0.38*
	Quercus mongolica	+0.74**	+0.55**	+0.52**	+0.46*

* Significant at the 0.05 level
** Significant at the 0.01 level

softwoods, as indicated by the correlation coefficient. Therefore, MOE in most softwoods appears to be less influenced by growth rate than MOR and Cmax. This is probably due to the poor relationship of MOE with specific gravity (Zhang 1994a, b).

In the two DPC species (*Betula platyphylla* and *Betula utilis*), although growth rate has no significant influence on both specific gravity and the mechanical properties, its effect on the mechanical properties is larger than on specific gravity, as indicated by the correlation coefficient. In the two poplar species, growth rate shows a very little influence on both specific gravity and the mechanical properties. As shown in Figs. 3 and 4, the physico-mechanical properties in *Populus tomentosa* tend to be more or less constant with increasing growth rate. As in the poplar species, growth rate has little influence on specific gravity and the mechanical properties in two RPC species (*Castanopsis carlessi* and *Castanopsis fargessii*). But it is different in the two ring-porous oak species (*Quercus aliena* and *Quercus mongolica*). Both specific gravity and the mechanical properties in the oak species increase remarkably with increasing growth rate (Table 2, Figs. 5 and 6).

So voluminous papers on the relationship of wood specific gravity with growth rate have been published, but the results reported are so controversial that various

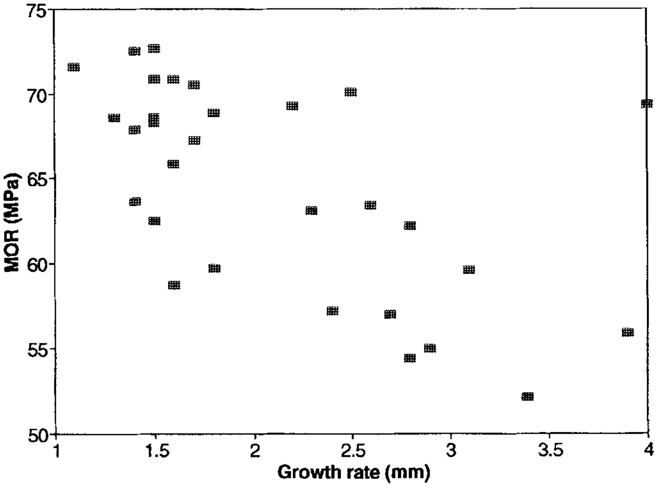

Fig. 2. MOR and Cmax in relation to growth rate in *Abies nephrolepis*

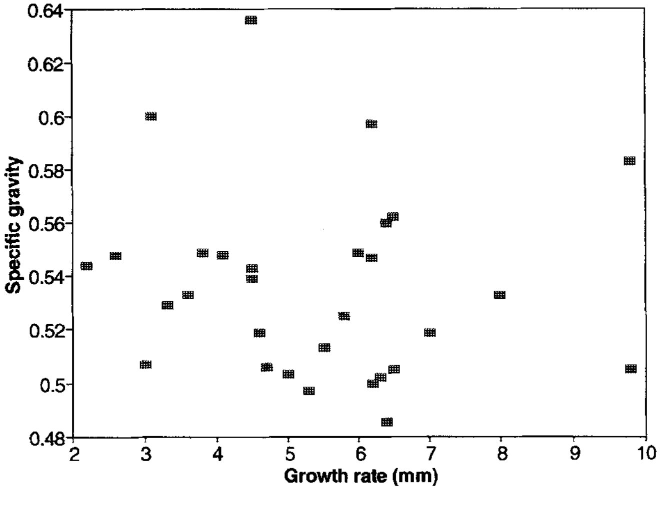

Fig. 3. Specific gravity in relation to growth rate in *Populus tomentosa*

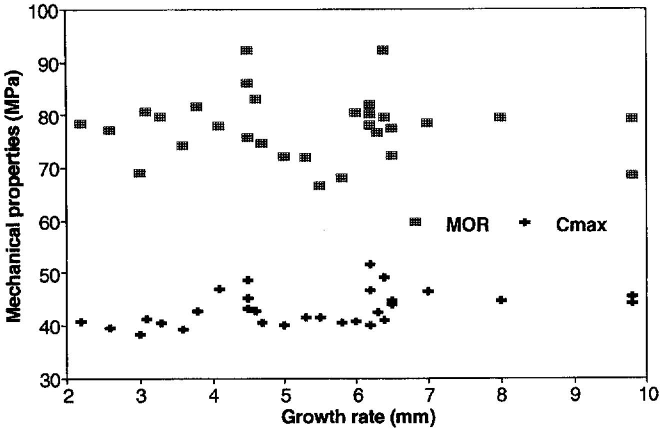

Fig. 4. MOR and Cmax in relation to growth rate in *Populus tomentosa*

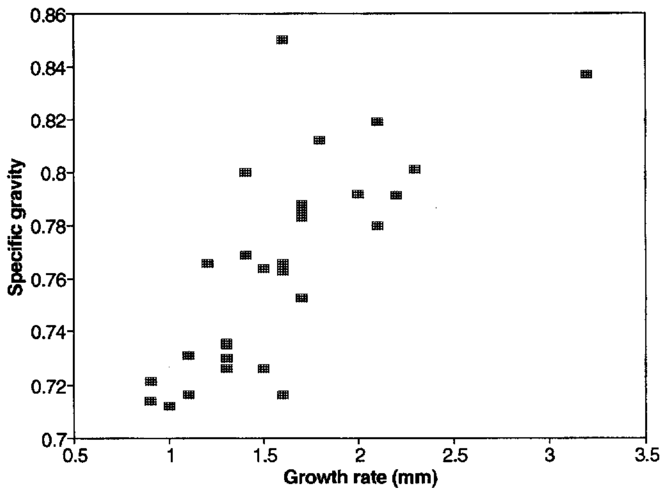

Fig. 5. Specific gravity in relation to growth rate in *Quercus mongolica*

conclusions can be found to support different opinions (Zobel and van Buijtenen 1989). Zobel and van Buijtenen (1989) summarized that wood specific gravity in conifers like *Picea* and *Abies* appears to decrease with increasing growth rate, while there is generally little or no relationship between wood specific gravity and growth rate in the species such as Douglas-fir and larches. These results fit the generalization of the relationship in the two distinct softwood categories. But the result on the two hard pines appear to be different from that reported by Ladrach (1986). He stated that faster growth may result in lower wood specific gravity for species like *Abies* and *Picea*, but it does not affect wood specific gravity of many hard pines as well as hardwoods. The statistical results on the 4 DPC species are well supported by major review papers which summarized that there is little relationship between specific gravity and growth rate in diffuse-porous woods (Johnson 1942; Panshin et al. 1964; Hillis and Brown 1978; Zobel and van Buijtenen 1989). Numerous reports cited by Panshin et al. (1964), Panshin and de Zeeuw (1980) and Zobel and van Buijtenen (1989) lend support to the general

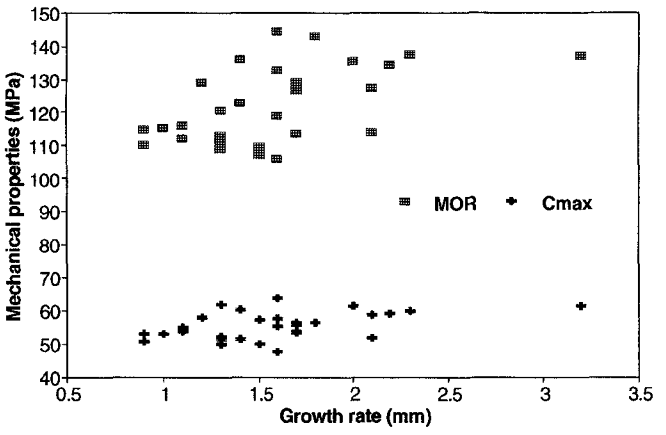

Fig. 6. MOR and Cmax in relation to growth rate in *Quercus mongolica*

relationship found in the RPC species in this study. Therefore, the generalization of the relationship between specific gravity and growth rate made in the present study overall seems to be largely supported by the previous studies.

Much less work has been done on wood mechanical properties in relation to growth rate, and the work reported so far is mostly restricted to some important softwood species. Olson et al. (1947) also noticed that the differences in major mechanical properties between natural forest and plantation trees vary with species and mechanical properties studied. Preliminary work on *Picea abies* (Leban et al. 1992), a FSC species, indicates that the static bending properties decrease remarkably with increasing ring width. In *Cunninghamia lanceolata* and Korean larch, Cheng et al. (1960) and Cheng (1962) reported that wood mechanical properties of these two SSC species from fast-grown plantation were not appreciably lower than those from natural forest. These results lend support to the present study on the different influence of growth rate on wood mechanical properties in the two softwood categories. But the results available so far on different pines (Olson et al. 1947; Huang and Liu 1959; Cheng 1963; Boone and Chudnoff 1972; Pearson and Gilmore 1980; Pearson and Ross 1984; Bendtsen and Senft 1986) are quite controversial. The earlier controversial reports and the present study both suggest that the relationship of wood quality with growth rate in the genus *Pinus* is probably more complicated and may vary remarkably with species. Therefore, further studies on the relationship in this genus are necessary. Little research has been done on the influence of growth rate on mechanical properties in hardwoods. Bamber et al. (1982), based on their study on *Eucalyptus grandis*, concluded that wood from the fast-grown trees would not be inferior in strength to the wood grown at normal rate.

The remarkable differences in the relationships of the wood physico-mechanical properties with growth rate between individual species from the four distinct wood categories appear to be closely related to their remarkable difference in wood structure. More specifically, the relationship between ring width and its components (earlywood width and latewood width), to a large extent, determines the relationships of the physico-mechanical properties with growth rate. With increasing ring width (or growth rate), for instance, earlywood width in *Abies fabri* tends to increase proportionally, while latewood width increases a little. Latewood percent thus decreases remarkably with increasing ring width (figure omitted). Therefore, specific gravity of the whole ring will decrease more or less due to the decreased percentage of the higher-density latewood (in the sense of the earlywood). A similar case was noticed in other FSC species as well as the two hard pines. In *Larix* species, however, latewood width tends to increase proportionally with increasing ring width. As a result, latewood percent tends to be more or less constant regardless of ring width (figure omitted). A similar case holds true in the DPC species. But the relationship between ring width and its components in some ring-porous woods appears to be quite different. As reported by many studies on oak species (Polge and Keller 1973; Wheeler 1987; Zhang 1990, 1992; Zhang and Zhong 1991; Zhang et al. 1993), earlywood width in the ring-porous oak species tends to increase little with increasing ring width. Latewood percent thus tends to increase appreciably with increasing ring width. Therefore, specific gravity as well as mechanical properties in these species will increase more or less with increasing growth rate. This case, however, does not necessarily hold true in other ring-porous species like *Castanopsis fargesii* and *Castanopsis carlessi.*

Limited information available so far (Dorn 1969; Anonymous 1962; Weiner and Roth 1966; Megraw 1985, 1986; Zobel and van Buijtenen 1989; Zhang and Morgenstern 1995a; 1995b) suggests that genetic and silvicultural manipulations, to some extent, may influence the relationship of wood properties with growth rate. Although a strong correlation between wood density and growth rate was reported in black spruce (*Picea mariana*) by Zhang and Morgenstern (1995a), for instance, they (1995b) meanwhile noticed that the strong negative correlation did not exist in all the 40 families studied. In other words, no correlation or even a weak positive correlation can be found in some families studied. This clearly shows to the tree breeders that even in a species where a negative correlation between growth rate and wood density exists it is still possible to select the trees which not only grow fast but maintain high wood density. A similar case was reported by Dorn (1969) who found growth rate has a larger effect on wood properties in some provenances of *Pinus sylvestris* than in others. The variation of the relationship between wood density and growth rate with silvicultural manipulations was well documented by Zobel and van Buijtenen (1989). They summarized that combined fertilization and thinning increase growth rate and frequently lower specific gravity, but this reduction is primarily associated with fertilization and does not occur following thinning alone. This clearly indicates that both fertilization and thinning are able to accelerate tree growth but they have different effects on wood specific gravity. This further implies that the influence of growth rate on wood properties is dependent upon its cause as well (Zobel and van Buijtenen 1989). Earlier studies suggest that the relationship of wood physico-mechanical properties with growth rate in a species, to some extent, may vary with environmental factors (e.g., location, site conditions). For instance, a strong negative correlation between wood density and growth rate was reported in black spruce grown in New Brunswick (Zhang and Morgenstern 1995a), but no close relationship was found in many black spruce stands grown in Newfoundland (Hall 1984). Risi and Zeller (1960) also reported an undetectable relationship in black spruce grown on a Hylocomium-Cornus site type. Similar controversial results can be found in other species like many Pinus species (e.g., *P. caribaea, P. elliottii, P. koriensis, P. radiata, P. strobus, P. taeda*). For instance, a negative relationship (Nicholls and Wirght 1976; Matziris 1979; Bannister and Vine 1981; Cown and McConchie 1981), no relationship (Nicholls and Fielding 1964; Nicholls and Brown 1973; Bamber and Burley 1983), and a positive relationship (Fielding and Brown 1960) were all reported in *Pinus radiata*. The environmental influence appears to be one of the reasons why different results have been reached for the same species.

Most studies on wood properties in relation to growth rate are usually limited to the radial growth, while wood properties in relation to height growth has received little attention. Very few studies available so far (Allen 1977; Vargas-Hernandez and Adams 1991; Park et al. 1989; Zhang and Morgenstern 1995a) suggest that height growth in a species may have an appreciably less (negative) effect on wood specific gravity than the radial growth. Zhang and Morgenstern (1995a) found a smaller negative correlation of wood specific gravity with tree height (−0.35) than with tree diameter at breast height (DBH) (−0.41). Some studies (Squillace et al. 1962; Shelbourne et al. 1972; Sohn and Goddard 1974) even found a positive correlation between specific gravity and tree height in the species where a negative correlation exists between wood specific gravity and tree diameter. These genetic results suggest that in a tree breeding program of any species where a negative correlation exists between wood properties and tree diameter, selection for tree height rather than tree diameter may have an appreciably less negative effect or even a positive effect on wood quality.

How does growth rate influence wood mechanical properties

It is usually assumed that the influence of growth rate on wood mechanical properties in a species results from the affected wood specific gravity. However, the present study shows that growth rate in some species shows an appreciably larger effect on the mechanical properties than on specific gravity (see Table 2). A similar case exists in the species studied by Olson et al. (1947) as well. He found that major mechanical properties of the plantation-grown softwoods, compared to the published data for similar tests on natural forest trees, are appreciably lower, but the specific gravity values are quite comparable. Therefore, it appears that growth rate influences wood mechanical properties not entirely through affected wood specific gravity. In other words, the variation of wood mechanical properties due to growth rate at least in some species is not attributed entirely to the affected wood specific gravity. This implies that growth rate, in addition to its effect which can be accounted for by specific gravity (or called indirect effect through specific gravity in the sense of path analysis), may have additional influence on wood mechanical properties (which can not be explained by specific gravity).

This is clearly shown in Table 3 by comparing the amount of variation in the wood mechanical properties attributed to wood specific gravity alone (r^2, correlation coefficient squared) with that attributed to both specific gravity and growth rate (R^2-multiple correlation coefficient squared). Although specific gravity alone is able to explain large part of the variation in MOR (17% to 80%), growth rate and specific gravity together are able to account for a more or less higher percentage of the variation in almost all FSC species studied. This holds true in Cmax. MOE in most FSC species is poorly explained by specific gravity, but growth rate and specific gravity together are also able to account for a remarkably higher percentage of the variation than specific gravity alone (Table 3). Therefore, growth rate in the FSC species has an additional effect on the mechanical properties (which can not be accounted for by wood specific gravity) although large part of the variation in MOR and Cmax due to growth rate can be explained by the affected wood specific gravity. This case, to a lesser extent, applies to most DPC species (except *Populus cathayana*). But this does not hold true in the RPC species as well as the SSC species (except *Larix gmelini*). Therefore, it apears that the additional influence (which can not be accounted for by the affected specific gravity) varies remarkably with the wood category. In the RPC species as well as the SSC species, the additional influence is not appreciable. In these cases, the influence of growth rate on the mechanical properties can be attributed, to a very large extent, to the affected wood specific gravity. In the FSC species and the DPC species, however, the additional influence is quite remarkable so that the influence of growth rate on the mechanical properties cannot be explained in terms of the affected wood specific gravity. Therefore, the impact of growth rate on the wood mechanical

Table 3. Coefficient of determinations (r^2 and R^2, respectively) for single-variable (specific gravity) and two-variable (both specific gravity and growth rate) regression equations showing the amount of variation in the mechanical properties explained by specific gravity (SG) alone and by both specific gravity and growth rate (SG + GR) in individual species from 4 distinct wood categories

Category	Species	MOR		MOE		Cmax	
		SG	SG + GR	SG	SG + GR	SG	SG + GR
FSC	*Abies nephrolepis*	0.39	0.56	0.10	0.17	0.34	0.41
	Abies fabri	0.52	0.58	0.01	0.23	0.57	0.60
	Picea asperata	0.17	0.39	0.03	0.27	0.17	0.55
	Picea koraiensis	0.81	0.79	0.50	0.55	0.77	0.79
SSC	*Larix gmelini*	0.47	0.51	0.07	0.20	0.59	0.61
	Larix olgensis	0.14	0.10	0.05	0.00	0.51	0.47
	Pinus massoniana	0.86	0.86	0.07	0.03	0.87	0.87
	Pinus yunnanensis	0.85	0.85	0.73	0.73	0.80	0.80
DPC	*Betula platyphylla*	0.50	0.52	0.44	0.62	0.31	0.33
	Betula utilis	0.57	0.61	0.08	0.37	0.22	0.30
	Populus cathayana	0.27	0.22	0.17	0.11	0.17	0.11
	Populus tomentosa	0.37	0.33	0.02	0.00	0.31	0.50
RPC	*Castanopsis carlessi*	0.60	0.59	0.26	0.23	0.40	0.36
	Castanopsis fargesii	0.22	0.17	0.64	0.62	0.13	0.06
	Quercus aliena	0.54	0.55	0.73	0.71	0.37	0.38
	Quercus mongolica	0.74	0.74	0.66	0.65	0.51	0.49

properties in these species can not be estimated through the relationship of wood specific gravity with growth rate.

The results were further confirmed by path analysis (Table 4). As shown by the direct path coefficients, specific gravity in almost all species from the 4 distinct wood categories has a significant (or highly significantly) direct effect on both MOR and Cmax, and this, to a lesser extent, applies to MOE as well. This statistical result implies that as long as wood specific gravity is influenced significantly by growth rate, the mechanical properties will be significantly influenced as well because wood specific gravity has a significant (and direct) influence on the mechanical properties. In the sense of path analysis, the direct influence of wood specific gravity on the mechanical properties should be regarded as the indirect influence of growth rate on the mechanical properties (through wood specific gravity). In addition to the indirect influence of growth rate on the mechanical properties, growth rate, to a differing extent, shows a direct effect on the wood mechanical properties (rather than through specific gravity) which can not be explained by specific gravity (Table 4). This effect in almost all FSC species is significant statistically. This, to a lesser extent, applies to the DPC species. In the RPS species and the SSC (except *Larix gmelini*), however, the effect is not remarkable, and may be negligible in the RPC species. Therefore, the results revealed by path analysis further specify that the variation in the mechanical properties due to growth rate in both SSC and RPC species is attributed largely to the affected wood specific gravity, and thus there is no significant additional effect on the mechanical properties. In the FSC species and the DPC species, however, growth rate has a significant effect on the mechanical properties which can not be explained by specific gravity.

Table 4. Direct path coefficients of growth rate (GR) and specific gravity (SG) to MOR, MOE and Cmax showing the direct effects of growth rate and specific gravity on the three mechanical properties in individual species from 4 distinct wood categories

Category	Species	MOR		MOE		Cmax	
		GR	SG	GR	SG	GR	SG
FSC	*Abies nephrolepis*	−0.47**	+0.51**	−0.35*	+0.24	−0.35**	+0.50**
	Abies fabri	−0.31*	+0.62**	−0.56**	−0.10	−0.26*	+0.67**
	Picea asperata	−0.51**	+0.32*	−0.54**	0.00	−0.65**	+0.29*
	Picea koraiensis	−0.05	+0.86**	−0.44*	+0.38*	−0.25	+0.69**
SSC	*Larix gmelini*	−0.26	+0.65**	−0.44*	+0.21	−0.21	+0.74**
	Larix olgensis	−0.14	+0.35*	+0.11	−0.20	−0.04	+0.70**
	Pinus massoniana	+0.09	+0.99**	−0.23	+0.10	−0.02	+0.92**
	Pinus yunnanensis	−0.18	+0.80**	−0.16	+0.15**	−0.01	+0.97**
DPC	*Betula platyphylla*	−0.40	+0.62**	−0.65*	+0.82**	−0.27	+0.47**
	Betula utilis	−0.27*	+0.77**	−0.62*	+0.33	−0.36*	+0.49**
	Populus cathayana	+0.02	+0.52**	−0.02	+0.42*	+0.05	+0.41*
	Populus tomentosa	−0.01	+0.61**	+0.10	+0.14	+0.48**	+0.61**
RPC	*Castanopsis carlessi*	+0.11	+0.77**	−0.17	+0.52**	+0.09	+0.63**
	Castanopsis fargesii	−0.05	+0.58*	−0.03	+0.17**	+0.06	+0.31
	Quercus aliena	+0.20	+0.68**	+0.05	+0.84**	+0.23	+0.55**
	Quercus mongolica	−0.20	+0.99**	−0.18	+0.94**	−0.17	+0.84**

* Significant at the 0.05 level
** Significant at the 0.01 level

Both wood physical properties and mechanical properties are virtually determined by wood anatomical and chemical characteristics. Although wood specific gravity is able to explain large part of variation in wood mechanical properties because of the well-known relationship between them, specific gravity serves only as a relative measure of wood cell wall materials per unite volume from wood anatomical point of view (Panshin and de Zeeuw 1980; Zhang 1992). This physical property is hardly able to reflect some wood anatomical features (e.g., microfibrill angle, wood element composition, fibre morphology) and chemical characteristics. These wood characteristics, however, are closely related to wood mechanical properties (Kollmann and Côté 1968; Panshin and de Zeeuw 1980; Hillis 1989; Tsoumis 1991; Zhang 1992). Therefore, the influence of growth rate on wood mechanical properties sometimes can not be well explained in terms of affected wood specific gravity.

Conclusions

Based on the present study on 16 softwoods and hardwoods from 4 distinct wood categories, it is rational to conclude:

1. With increasing growth rate the wood mechanical properties in the FSC species decrease significantly, and this, to a lesser extent, applies to the SSC species. In the DPC species, growth rate has a very little influence on both specific gravity and the mechanical properties. In the RPC species, both specific gravity and the mechanical properties appear not to decrease, and in some species they even tend to increase.
2. Among the three mechanical properties studied, growth rate shows an appreciably less effect on MOE than on MOR and Cmax. Compared to specific gravity, however, the mechanical properties generally are more remarkably influenced by growth rate,

particularly in the FSC species. Therefore, the impact of growth rate on wood mechanical properties can not be estimated exactly through the relationship of wood specific gravity with growth rate.

3. Large part of the variation in the mechanical properties due to growth rate can be accounted for by the affected wood specific gravity. In addition to this effect (which can be accounted for by the wood specific gravity), growth rate, to a differing extent, still has an additional effect on the wood mechanical properties (which can not be explained by wood specific gravity). This effect is quite remarkable in the SFC species, and this, to a lesser extent, holds true in the DPC species. However, this effect is not remarkable in the SSC species and may be negligible in the RPC species.

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