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Stress-wave velocity of stems, dynamic Young's modulus of logs, and wood properties in two broad-leaved tree species

広葉樹 2 種における樹幹の応力波伝播速度，丸太の動的ヤング率および木材性質

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ABSTRACT

The objectives of this study are to obtain information about basic wood properties of broad-leaved tree species which are abundantly found in secondary forests in Japan to effectively utilize their wood resources. Growth characteristics (stem diameter at 1.3 m above the ground and tree height), and stress-wave velocity of stems were measured in two broad-leaved trees species, *Castanea crenata* Siebold et Zucc. and *Magnolia obovata* Thunb. naturally regenerated in a secondary forest. After harvesting trees, dynamic Young's modulus of logs and basic wood properties (oven-dry density, modulus of elasticity [MOE], modulus of rupture [MOR], and bending work) were determined. Mean stem diameter, tree height, and stress-wave velocity of stems were 27.3 cm, 16.8 m and 2.89 km/s for *C. crenata*, and 23.6 cm, 18.1 m and 3.29 km/s for *M. obovata*, respectively. Mean values of dynamic Young's modulus of logs were 8.08 and 8.90 GPa for *C. crenata* and *M. obovata*, respectively. Dynamic Young's modulus of logs gradually increased from bottom to a certain height, and then it gradually decreased toward the tree top in both species. Mean values of oven-dry density, MOE, MOR, and bending work in *C. crenata* and *M. obovata* were 0.55 g/cm^3, 8.78 GPa, 75.6 MPa and 7.6 N m, and 0.42 g/cm^3, 8.69 GPa, 73.7 MPa and 7.5 N m, respectively. No significant correlations were found between oven-dry density and bending properties, suggesting that prediction of bending properties by oven-dry density is difficult in both species.
Keywords: *Castanea crenata*, *Magnolia obovata*, stress-wave velocity, wood density, bending property

要　旨

本研究では，我が国の二次林に豊富に存在する広葉樹種から得られる木材資源を有効に活用するために，これらの樹種の基礎的な木材性質を明らかにすることを目的とした．成長特性（樹高 1.3 m 部位での幹直径および樹高）および樹幹の応力波伝播速度を二次林に生育したクリ（*Castanea crenata* Siebold et Zucc.）およびホオノキ（*Magnolia obovata* Thunb.）において測定した．伐採後，丸太の動的ヤング率および基礎的な木材性質（全乾密度，曲げヤング率［MOE］，曲げ強さ［MOR］および曲げ仕事量）を測定した．幹直径，樹高および樹幹の応力波伝播速度の平均値は，クリでは 27.3 cm，16.8 m および 2.89 km/s であり，ホオノキでは 23.6 cm，18.1 m および 3.29 km/s であった．また，丸太の動的ヤング率の平均値は，クリおよびホオノキでそれぞれ 8.08 および 8.90 GPa であった．丸太の動的ヤング率は，基部からある樹高位置まで徐々に増加し，その後頂端に向かって徐々に減少する傾向が認められた．クリおよびホオノキにおける平均全乾密度，MOE，MOR および曲げ仕事量は，それぞれ，0.55 g/cm^3，8.78 GPa，75.6 MPa，7.6 N m，および 0.42 g/cm^3，8.69 GPa，73.7 MPa，7.5 N m であった．両樹種において，全乾密度と曲げ物性の間に有意な相関関係は認められなかった．このことから，本実験で使用した樹種において，曲げ物性を全乾密度により推定することは難しいと考えられる．
キーワード : クリ（*Castanea crenata*），ホオノキ（*Magnolia obovata*），応力波伝播速度，木材密度，曲げ物性

1. Introduction

Until 1960's, firewood and charcoal were commonly used as fuel for cooking, heating and others in personal houses in Japan. The firewood and raw materials for charcoal were mainly obtained from the secondary forests mainly composed of broad-leaved tree species. After 1960's, fossil fuels, such as liquid propane gas, kerosene and others have been used as fuel in personal houses (Kanazawa et al. 2009). Thus, demands were dramatically decreased for firewood and charcoal. Decreasing the demands of firewood and charcoal led increases of wood resources in abandoned secondary forests. To manage the abandoned secondary forests, considering the utilization of hardwood resources from the forests is important.

In Japan, basic wood properties have been mainly investigated for plantation softwood species, such as *Cryptomeria japonica* (Fukuhara et al. 1983; Hirakawa et al. 1997; Kijidani and Kitahara 2003; Nishimura et al. 2003; Ishiguri et al. 2009; Yamashita et al. 2009), *Chamaecyparis obtusa* (Tsushima et al. 2006; Kijidani et al. 2012), and *Larix kaempferi* (Zhu et al. 2000; Koizumi et al. 2005; Fukatsu et al. 2015). On the other hand, available data on wood properties are not so much for broad-leaved tree species found in the secondary forests (Sawabe and Suzuki 1983; Furukawa et al. 1983). To effectively utilize the hardwood resources, studies on wood properties are needed for broad-leaved tree species.

The objectives of this study are to obtain the basic information about wood properties of broad-leaved tree species abundantly found in secondary forests in Japan. In this study, two broad-leaved tree species, *Castanea crenata* Siebold et Zucc. and *Magnolia obovata* Thunb. were used. After measuring the growth characteristics and stress-wave velocity of stems, total six trees (three trees in each species) were harvested for determining dynamic Young's modulus of logs and wood properties such as bending properties.

2. Materials and methods

2.1 Materials

Two broad-leaved tree species, *Castanea crenata* Siebold et Zucc. and *Magnolia obovata* Thunb. were used in the present study. *Castanea crenata* is ring-porous wood and *M. obovata* is diffuse-porous wood. These trees were naturally regenerated in the secondary forests located in Funyu Experimental Forest, School of Agriculture, Utsunomiya University (36°46' N, 139°49' E, ca. 340 m above sea level).

2.2 Growth characteristics and stress-wave velocity of stems

Growth characteristics and stress-wave velocity were measured for 13 and 12 trees for *C. crenata* and *M. obovata*, respectively. Stem diameter at 1.3 m above the ground was measured by tape measure (F10-02DM, KDS). A commercial handheld height meter (Vertex IV, Haglöf) were employed to measure tree height. Stress-wave velocity of stems were determined by a handheld stress-wave timer (Fakopp microsecond timer, Fakopp Enterprise) with the method described in the previous study (Ishiguri et al. 2007, 2008). The sensors were set at 0.5 and 1.5 m above the ground. Stress-wave propagation time was measured and then the distance between sensors (1 m) was divided by the time for calculating the stress-wave velocity.

2.3 Dynamic Young's modulus of logs

After measuring growth characteristics and stress-wave velocity of stems, six trees (three trees in each species) were selected based on mean stem diameter at 1.3 m above the ground in each species. After harvesting the six trees, the logs with 2 m in length were collected from 1.3 m above the ground to tree top. Number of annual rings at 1.3 m above the ground ranged from about 30 to 50 in six harvested trees. Total, 13 and 15 logs were obtained in *C. crenata* and *M. obovata*, respectively. Dynamic Young's modulus was measured by longitudinal vibration method (Sobue 1986). One end of the logs was hit by a small hammer, and then created sound was captured by accelerometer (PV-85, RION) set on another end of the logs. The first resonance frequency was determined by a handheld fast Fourie transform analyzer (AD-3527, A&D). For calculating the dynamic Young's modulus, density at testing was also determined by measuring the both end diameters, length, and weight.

2.4 Wood properties

Logs with 50 cm in length were collected from 0.8 to 1.3 m above the ground level from the harvested six trees. Bark to bark radial boards with pith (30 mm in thickness) were obtained from the logs. After air-drying, the boards were planed to 20 mm in thickness, and then two pith to bark radial boards were prepared. The pith to bark boards were cut again at 20 mm interval from pith to prepare the static bending test specimens (ca. 20 (T) by 20 (R) by 320 (L) mm). The bending test was conducted by a universal testing machine (MSC-5/200-2, Tokyo Testing Machine) with 280 mm span. The load was applied at the radial surface of center of specimens with speed of 5 mm/min. The load and deflection data was recorded in computer and the following bending properties were determined: modulus of elasticity (MOE), modulus of rupture (MOR), and bending work. For calculating the bending work, proposal limit was regarded as the point of which two-third values of maximum load. Then, area was determined for load-deflection diagram obtained by the static bending test. After the bending test, small specimens (ca. 20 by 20 by 20 mm) were obtained from the specimens without any damages in bending test for calculating moisture content at testing and oven-drying density.

2.5 Data analysis

All data analysis were conducted by using a software (R version 4.0.2, R Core Team 2020). Correlation coefficients among properties were calculated by 'cor.test' in R software.

3. Results and discussion

3.1 Growth characteristics and stress-wave velocity of stems

Table 1 shows stem diameter, tree height, and stress-wave velocity of stem. Mean stem diameter and tree height were 27.3 cm and 16.8 m for *C. crenata*, and 23.6 cm and 18.1 m for *M. obovata*, respectively. Although tree age was unknown, *C. crenata* trees showed larger stem diameter with shorter tree height compared to *M. obovata* trees.

Stress-wave velocity ranged from 2.55 to 3.27 km/s for *C. crenata*, and 2.89 to 3.60 km/s for *M. obovata*, respectively. In trees grown temperate zone, Tanabe et al. (2020) reported that stress-wave velocity of *Lithocarpus edulis* trees grown in Chiba, Japan (estimated tree age =30 to 60 years old) ranged from 3.00 to 4.32 km/s. Prasetyo et al. (2015a) reported that mean values of stress-wave velocity of stems in half-sib families planted in three different initial spacings ranged from 2.71 to 3.08 km/s for 20-year-old *Zelkova serrata* trees. The results obtained in the present study showed relatively slower stress-wave velocity compared to *L. edulis* trees, but similar with 20-year-old *Z. serrata* trees.

In softwood species, weak negative or no significant correlations were obtained between stem diameter and stress-wave velocity of stems (Ikeda and Arima 2000; Ishiguri et al. 2008; Tumenjargal et al. 2018), suggesting that faster radial growth rate did not always lead to production of wood with lower strength properties. Similar results were also found in broad-leaved tree species grown in tropics (Ishiguri et al. 2007, 2016; Pertiwi et al. 2017). In the present study, no significant correlations were found between growth characteristics and stress-wave velocity of stems (Figure 1). Thus, it is concluded that stress-wave velocity of stem might be independent from growth characteristics in *C. crenata* and *M. obovata*.

3.2 Logs

Mean values of dynamic Young's modulus of logs in each individual trees ranged from 7.30 to 9.29 GPa for *C. crenata*, and 8.68 to 9.14 GPa for *M. obovata* (Table 2). Mean values of three trees were 8.08 and 8.90 GPa for *C. crenata* and *M. obovata*, respectively. Prasetyo et al. (2015b) reported that mean value of static MOE of 20-year-old *Z. serrata* logs was 6.43 GPa. In general, dynamic Young's modulus showed about 5 to 10% higher values than the MOE value (Ishimaru et al. 2017). Thus, although the tree age might be different, dynamic Young's modulus of logs obtained in the present study relatively higher values compared to 20-year-old *Z. serrata* logs.

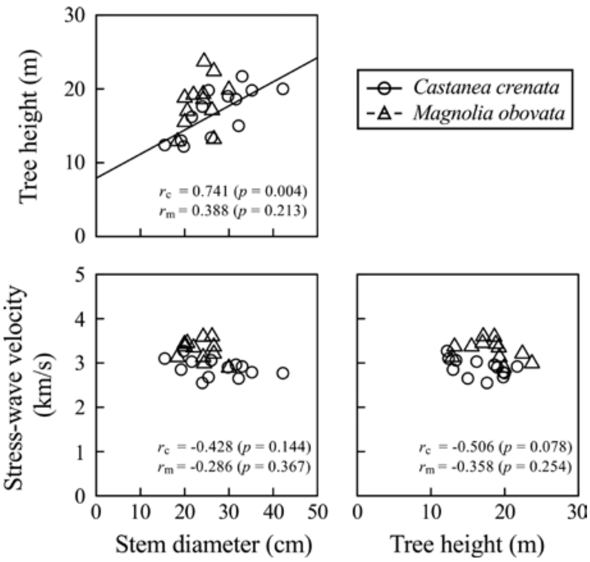

Figure 1 Relationships between stem diameter, tree height, and stress-wave velocity of stems in two species

Note: *r*, correlation coefficient; *p*: probability; c, *Castanea crenata*; m, *Magnolia obovata*. Solid line indicates regression lines in *Castanea crenata*.

Table 1 Stem diameter, tree height and stress-wave velocity of stems

Species	*n*	D (cm)				TH (m)				SWV (km/s)			
		Mean	SD	Min.	Max.	Mean	SD	Min.	Max.	Mean	SD	Min.	Max.
C. crenata	13	27.3	7.5	15.5	42.2	16.8	3.3	12.2	21.7	2.89	0.20	2.55	3.27
M. obovata	12	23.6	3.5	18.4	30.0	18.1	3.2	12.9	23.7	3.29	0.22	2.89	3.60

Note: *n*, number of trees; D, stem diameter at 1.3m above the ground; TH, tree height; SWV, stress-wave velocity of stems; SD, standard deviation; Min., minimum; Max., maximum.

Table 2 Green density and dynamic Young's modulus of logs in two species

Property	*Castanea crenata*				*Magnolia obovata*			
	No. 1	No. 2	No. 3	Mean/Total	No. 1	No. 2	No. 3	Mean/Total
n	6	4	3	3	5	6	4	3
GD (g/cm^3)	0.91 (0.03)	0.89 (0.02)	0.85 (0.05)	0.88 (0.03)	0.72 (0.02)	0.72 (0.07)	0.75 (0.04)	0.73 (0.02)
DMOE (GPa)	7.30 (1.32)	9.29 (0.35)	7.66 (1.35)	8.08 (1.06)	8.68 (0.47)	9.14 (0.63)	8.88 (1.29)	8.90 (0.23)

Note: *n*, number of logs in a tree (No. 1, 2, or 3) or number of trees in 'Mean/Total' column; GD, green density; DMOE, dynamic Young's modulus. Values in parenthesis after mean values indicate standard deviation.

Figure 2 shows longitudinal variations of dynamic Young's modulus of logs. In both species, dynamic Young's modulus of logs increased from first log (collected from 1.3 to 3.3 m above the ground) to second (3.3 to 5.3 m above the ground) or third (5.3 to 7.3 m above the ground) logs, then gradually decreased with increase of height position. Similar longitudinal variations of dynamic Young's modulus were found in softwood species: dynamic Young's modulus of *C. japonica* logs showed peak values at a certain height and then it gradually decreased toward the tree top (Hirakawa et al. 1997). Hirakawa et al. (1997) reported that microfibril angle of S_2 layer in tracheid affected these longitudinal tendencies. Thus, longitudinal variations of logs in this study also might be related to the microfibril angle of wood fibers. Further research is needed to identify the effects of microfibril angle on dynamic Young's modulus of logs in broad-leaved tree species.

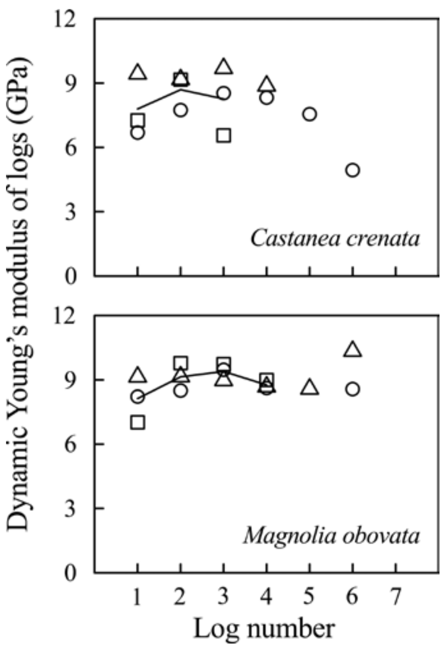

Figure 2 Longitudinal variations of dynamic Young's modulus of logs in two species

Note: Each symbol indicates each individual tree. Solid lines indicate mean values in each species.

3.3 Wood properties

Results of bending test were shown in Table 3. Wood Technology and Wood Utilization Division (1982) reported that oven-dry density, MOE, and MOR were 0.48 (sapwood) - 0.52 (heartwood) g/cm^3, 8.77GPa and 75.2 MPa for *C. crenata*, and 0.43 (heartwood) - 0.45 (sapwood) g/cm^3, 7.64 GPa and 74.7MPa for *M. obovata*. Mean values obtained in the present study were similar to those reported by Wood Technology and Wood Utilization Division (1982). On the other hand, mean values of bending work in *C. crenata* and *M. obovata* were 7.6 and 7.5 N m, respectively (Table 3). In *C. japonica*, bending work in juvenile wood and mature wood was 8.6 and 6.0 N m (Ishiguri et al. 2009). Although the *C. japonica* is a softwood, mean values of bending work in two broad-leaved tree species used in the present study were similar to those in *C. japonica*.

Radial variations of oven-dry density and bending properties were shown in Figure 3. Oven-dry density was almost constant from pith to bark in *C. crenata*, but it gradually decreased in *M. obovata*. All bending properties determined in the present study gradually increased from pith to bark in *C. crenata*. On the other hand, in *M. obovata*, it gradually increased and then decreased toward bark side.

In general, wood density is positively related with bending properties (Ishimaru et al. 2017). In the present study, as shown in Figure 4, no significant correlations were found between oven-dry density and bending properties. Thus, bending properties might be related with other factors, such as microfibril angle of S_2 layer in wood fibers. It has been reported that MOE is positively correlated with MOR in many species (Ishimaru et al. 2017). This tendency is also true for the results in the present study (Figure 4). On the other hand, bending work was significantly correlated with MOR in only *C. crenata*. Ishiguri et al. (2009) reported that,

Table 3 Bending properties in two species

Property	*Castanea crenata*				*Magnolia obovata*			
	No. 1	No. 2	No. 3	Mean/Total	No. 1	No. 2	No. 3	Mean/Total
n	4	5	4	3	4	4	4	3
MC (%)	12.5 (0.2)	12.6 (0.2)	11.9 (0.3)	12.3 (0.4)	11.3 (0.2)	11.0 (0.2)	11.1 (0.2)	11.1 (0.2)
OD (g/cm^3)	0.60 (0.03)	0.53 (0.02)	0.53 (0.02)	0.55 (0.04)	0.40 (0.02)	0.41 (0.03)	0.45 (0.03)	0.42 (0.03)
MOE (GPa)	8.15 (2.77)	8.32 (1.37)	9.87 (0.72)	8.78 (0.95)	8.27 (0.41)	9.01 (0.89)	8.79 (0.37)	8.69 (0.38)
MOR (MPa)	70.8 (39.8)	79.0 (11.1)	76.9 (19.0)	75.6 (4.3)	69.9 (5.5)	73.7 (5.5)	77.5 (3.6)	73.7 (3.8)
W (N m)	8.4 (7.4)	8.1 (2.2)	6.2 (4.1)	7.6 (1.2)	7.8 (0.1)	6.6 (0.9)	8.2 (1.0)	7.5 (0.8)

Note: *n*, number of specimens from radial position in a tree (No. 1, 2, or 3) or number of trees in 'Mean/Total' column; MC, moisture content at bending testing; OD, oven-dry density; MOE, modulus of elasticity; MOR, modulus of rupture; W, bending work. Values in parenthesis after mean values indicate standard deviation.

in *C. japonica*, significant correlation was found between MOR and bending work in mature wood, but not in juvenile wood. They also pointed out that bending properties of *C. japonica* were mainly affected by wood density in juvenile wood, and by microfibril angle in mature wood. Thus, further research is needed for relationship between microfibril angle and bending properties in hardwoods.

4. Conclusions

In the present study, growth characteristics, stress-wave velocity of stems, dynamic Young's modulus of logs, and basic wood properties were investigated in two broad-leaved tree species (*C. crenata* and *M. obovata*) naturally regenerated in a secondary forest. Stress-wave velocity of stems was 2.89 and 3.29 km/s for *C. crenata* and *M. obovata*, respectively. Weak negative, but no significant correlations were found between growth characteristics and stress-wave velocity of stems in both species. Dynamic Young's modulus of logs gradually increased from bottom to a certain height positions, and then it gradually decreased. Mean values of dynamic Young' modulus of logs were 8.08 and 8.90 GPa for *C. crenata* and *M. obovata*, respectively. Mean values of oven-dry density, MOE, MOR, and bending work in *C. crenata* and *M. obovata* were 0.55 g/cm^3, 8.78 GPa, 75.6 MPa and 7.6 N m, and 0.42 g/cm^3, 8.69 GPa, 73.7 MPa and 7.5 N m, respectively. Significant positive correlations were not found between oven-dry density and bending properties, suggesting that prediction of bending properties by oven-dry density is difficult in both species. Thus, further research is needed to clarify the suitable factors which can predict the bending properties in both species.

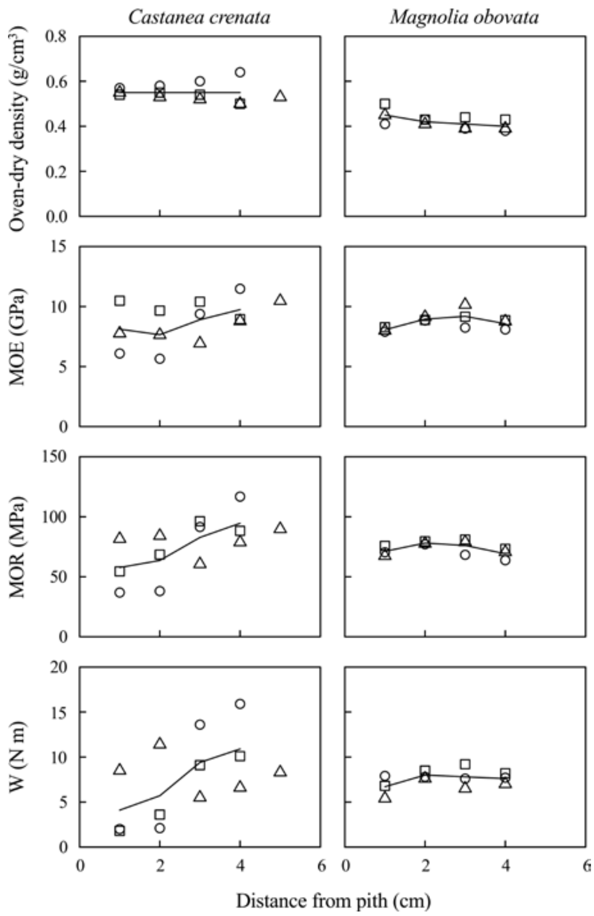

Figure 3 Radial variations of oven-dry density and bending properties in two species

Note: MOE, modulus of elasticity; MOR, modulus of rupture, W, bending work. Each symbol indicates each individual tree. Solid lines indicate mean values in each species.

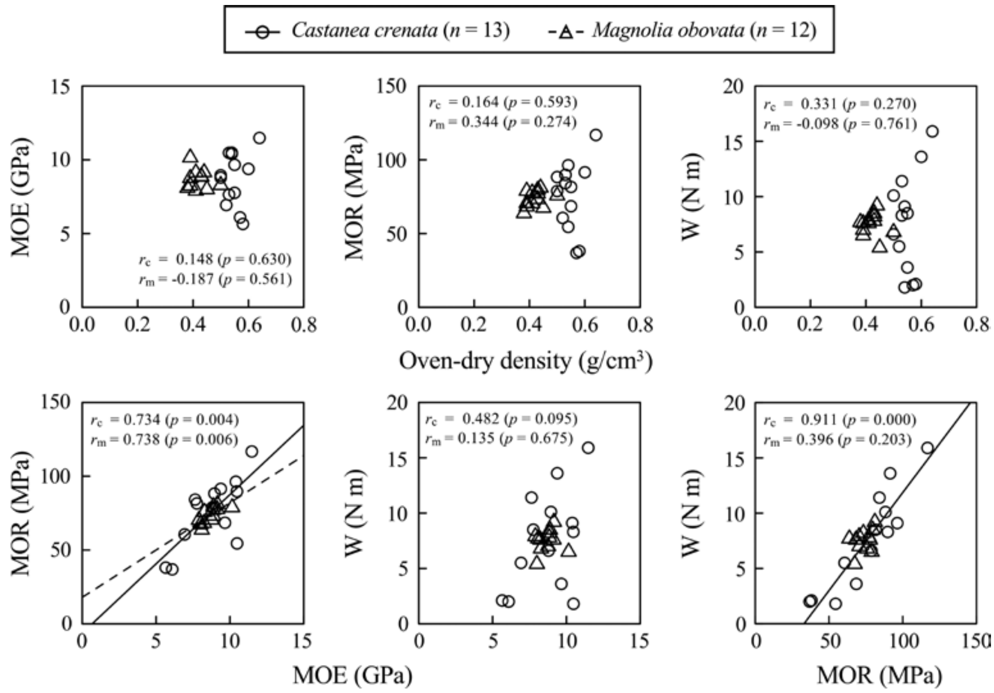

Figure 4 Relationships between oven-dry density and bending properties in two species

Note: *n*, Number of specimens; *r*, correlation coefficient; *p*, probability; c, *Castanea crenata*; m, *Magnolia obovata*; MOE, modulus of elasticity; MOR, modulus of rupture; W, bending work. Solid and dotted lines indicate regression lines in *Castanea crenata* and *Magnolia obovata*, respectively.

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