

1 **Allometric scaling of leaf mass based on the pipe model theory for woody**  
2 **plant species**

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8 Kazuharu Ogawa

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13 *Laboratory of Forest Ecology, Graduate School of Bioagricultural Sciences, Nagoya University,*

14 *Nagoya 464-8601, Japan*

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17 Tel: +81-52-789-4071

18 Fax: +81-52-789-5014

19 E-mail: [kazogawa@agr.nagoya-u.ac.jp](mailto:kazogawa@agr.nagoya-u.ac.jp)

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22 ORCID: 0000-0001-8283-660X

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26 **Abstract**

27 There is an exceptional case in which Shinozaki's pipe model predictions should not explain that  
28 the allometric scaling exponent between foliage mass and stem diameter at the crown base is  
29 bigger than 2 empirically. This study proposes an allometric scaling model with components  $f$   
30 and  $b$ , which are the scaling exponent between the sapwood area and stem cross-sectional area  
31 and foliage mass and the stem cross-sectional area at crown base, respectively. The scaling  
32 exponent  $f$  of sapwood area vs. stem diameter at the crown base has no effect on leaf mass vs.  
33 stem diameter at the crown base, while the scaling exponent  $b$  has effects on leaf mass vs. stem  
34 diameter at the crown base. Because the value of  $b$  is greater than unity, this scaling model  
35 predicts that the diameters of conduits at the crown base widen with tree size, indicating tip-base  
36 widening of conduits. Because the proportion of sapwood area remains constant (or  $f=0$ ) across  
37 sizes, the assumption of Shinozaki's pipe model theory appears to apply to the case  $f=0$ .

38

39 **Keywords** allometric scaling, conduit diameter, leaf mass, pipe model theory, stem diameter at  
40 crown base, sapwood area

41

42 **Author Contribution Statement:** The author (KO) designed research, collected the data,  
43 analyzed them, and wrote the paper.

44

45 **Conflict of Interest:** The author (KO) declares that he has no conflict of interest.

46

## 47 **Introduction**

48 According to the classical pipe model theory developed by Shinozaki et al. (1964a, b), the leaf  
49 mass of individual trees is closely related to the stem diameter at the crown base, which is  
50 therefore a useful metric for estimating the leaf mass. Based on the pipe model theory, the  
51 allometric scaling exponent between leaf mass and stem diameter at the crown base is  
52 theoretically 2. However, there is an exceptional case when the allometric scaling exponent is  
53 greater than 2, which occurs when the proportionality of leaf mass to the square of the stem  
54 diameter at the crown base tends to segregate canopy trees from suppressed trees (Shinozaki et  
55 al. 1964b). Therefore, the present models have a limited (Kobayashi and Maskawa 1973) ability  
56 to express the mechanism of the allometric scaling between leaf mass and stem diameter at the  
57 crown base.

58 Several subsequent models have been developed by distinguishing between active and  
59 disused pipes, and by considering sapwood area equivalent to active pipe area, since the foliage  
60 mass should be closely related to the sapwood area (as reviewed by Lehnebach et al. 2018). As a  
61 result of these approaches, the allometric scaling exponent becomes unity in the leaf mass–  
62 sapwood area relationship, in which the pipe model ratio, or the ratio of foliage mass to the  
63 sapwood ratio at the crown base, which was proposed in lieu of the specific pipe length  
64 (Shinozaki et al. 1964a), should be constant (e.g. Whitehead et al. 1984, Shelburne et al. 1993,  
65 Mencuccini and Grace 1995, Mäkelä et al. 1995, Vanninen et al. 1996, Meadows and Hodges  
66 2002).

67 The pipe model theory is one of the most important approaches for understanding the  
68 hydraulic architecture of trees. However, it has major limitations that suggest that the pipe  
69 structure as proposed by Shinozaki et al. (1964a, b) cannot be found in an actual tree. The most  
70 critical assumption relies on the fact that the pipes of the basic elements of the plant vascular  
71 system are cylindrical, i.e., the conduit diameter does not change axially. However, the main  
72 property of the hydraulic system of trees is to have tip–base widening of the conduits (e.g., West  
73 et al. 1999; Anfodillo et al. 2006; Petit and Anfodillo 2009; Savage et al. 2010; Olson et al. 2014,  
74 2018, 2021; Koçillari et al. 2021). Therefore, this universal, but ineludible, pattern has a  
75 profound effect on the relationship between foliage mass and stem diameter.

76           Recently, Ogawa (2015) examined the allometric scaling exponent between leaf mass and  
77 stem diameter at the crown base among several forest trees, and reported values greater than 2  
78 for all species. Ogawa (2015) applied the stratified clipping method (Monsi and Saeki 1953) to  
79 conduct a mathematical analysis of the mechanism that causes the scaling exponent to exceed 2,  
80 and found that the scaling exponent is controlled by the size dependence of the specific pipe  
81 length, which is related to competition among forest trees and can be used as an index of the  
82 degree of suppression by larger trees.

83           However, it is not known how the pipe model ratio (cf. Lehnebach et al. 2018) is related  
84 to the allometric scaling exponent between leaf mass and stem diameter at the crown base in  
85 classical pipe model theory (cf. Shinozaki et al. 1964a, b). That is, if the pipe model ratio is  
86 constant, under what conditions does the classical pipe model theory hold? Because the pipe  
87 model ratio is related to the stem sapwood area, while the classical pipe model theory is related  
88 to the stem cross-sectional area, the proportion of sapwood area might explain why the  
89 allometric scaling exponent exceeds 2 by linking the pipe model ratio and classical pipe model  
90 theory. In addition to the sapwood area proportion, tip-to-base xylem conduit widening should be  
91 considered for the exceptional cases in which the pipe model predictions should not explain the  
92 correlation between leaf mass and diameter of the stem using experimental data.

93           The stratified clipping method is a time- and labor-intensive approach, especially for  
94 trees, for which relevant data are very limited. Therefore, to clarify the factors that control the  
95 allometric scaling exponent of leaf mass in the pipe model, the present study provides a simple  
96 allometric scaling model of leaf mass based on the leaf mass and stem diameter at the crown  
97 base, considering the hydraulic vessel system, such as the proportion of sapwood area, and the  
98 conduit diameter.

99           All data used in this study were collected from four stands of hinoki cypress  
100 (*Chamaecyparis obtusa* (Sieb. et Zucc.) Endl.) located in Aichi Prefecture, central Japan (Table  
101 1, cf. Hagihara et al. 1993), as follows:

102 **1) Nagoya.** This stand was established in an experimental forest of Nagoya University on flat  
103 terrain at 50 m a.s.l.. No artificial management has been performed since the plantation was  
104 established. Since the canopy was fully closed, undergrowth vegetation was nearly absent.

- 105 **2) Inabu.** This stand is located at Nagoya University Forest on a 35° north-facing slope at an  
106 elevation of 500 m a.s.l.. Artificial management was performed only immediately after the  
107 plantation was established. Undergrowth vegetation was nearly absent.
- 108 **3) Hourai.** This stand is located at the Aichi Prefectural Forest Research Institute on an 18.5°  
109 northwest-facing slope at 435 m a.s.l. No artificial management was performed in the stand  
110 within the 20 years preceding the survey. Undergrowth vegetation was nearly absent.
- 111 **4) Dando.** This stand is located in a national forest administered by the Shinshiro District Forest  
112 Office and Nagoya Regional Forest Office on a 25° west-facing slope at 900 m a.s.l.  
113 Thinning was performed 4 years prior to the survey. Ground vegetation consisted of a dense  
114 population of suzudake (*Sasamorpha borealis* [Hack.] Nakai) that was ca. 2 m tall.

115

#### 116 *Measurement of tree size and mass*

117 After the sample trees were felled, the tree height, crown base height, stem diameter at a height  
118 of 1.3 m above the ground (DBH), and stem diameter at the crown base ( $D_B$ ) were measured.

119 Following the tree size measurements, the stratified clipping method (Fig. 1) was applied  
120 to the felled trees (Monsi and Saeki 1953). The trees were stratified into several vertical strata  
121 defined at 0–0.3, 0.3–1.3 m, and then 1.0 m intervals from ground level to the top of the crown.  
122 The stems, branches, and leaves from each stratum were clipped separately from all layers. The  
123 stems, branches, and leaves in each stratum were weighed. The roots were washed and weighed  
124 following excavation.

125 Samples were collected from each stratum to estimate the dry/fresh mass ratio for each  
126 organ, including the roots. The samples were dried in ventilated ovens at 85°C for a few days,  
127 desiccated at room temperature, and then weighed. Fresh mass was converted to dry mass to  
128 obtain stem, branch, leaf, and root values per tree using their respective ratios.

129

#### 130 *Measurement of sapwood area at the crown base*

131 Measurements of sapwood area at the crown base (Adu-Bredu and Hagihara 1996) were  
132 performed using 12-year-old *C. obtusa* trees (Table 1) as follows: 13 trees were harvested, and  
133 stem discs were removed from the crown base (thickness, 1.5–4.0 cm). Sapwood was

134 differentiated from heartwood by color and staining with ferric chloride solution (e.g., Ryan  
135 1989).

136 The disc circumference was measured using a steel measuring tape, and the heartwood  
137 circumference was measured using a Digital Curvimeter (S-880; Uchida, Tokyo, Japan). The  
138 sapwood cross-sectional area was calculated as the difference between the stem and heartwood  
139 cross-sectional areas, and the proportion of sapwood area was determined as the ratio of the  
140 sapwood cross-sectional area to the stem cross-sectional area.

141

## 142 *Model descriptions*

143 **Allometric scaling of leaf mass:** Assuming that the pipe model ratio is constant at the crown  
144 base, i.e., an allometric scaling exponent of unity between the leaf mass and the sapwood area at  
145 the crown base, the leaf mass is not proportional to the sapwood area at the crown base as long as  
146 the proportion of the sapwood area is greater in larger trees than in smaller trees. Under this  
147 condition, the following model supports  $m_L-D_B^2$  allometry, with a scaling exponent that tends to  
148 be greater than unity in several woody species (Ogawa 2015).

149 According to traditional pipe model theory (cf. Lehnebach et al. 2018), the stem cross-  
150 sectional area at the crown base and the sapwood area are denoted as  $A_B \left( = \frac{\pi}{4} D_B^2 \right)$  and  $A_S$  (cm<sup>2</sup>),  
151 respectively, where the leaf mass  $m_L$  (kg) is assumed to be proportional to  $A_S$  as follows:

152

$$153 \quad m_L = aA_S. \quad (1)$$

154

155 where  $a$  is a constant equivalent to the pipe model ratio at the crown base. This model has more  
156 generality in the  $m_L-A_S$  relation of Eq. (1), so that the leaf mass  $m_L$  (cm<sup>2</sup>) scales as  $A_S^b$ ,

157

$$158 \quad m_L = aA_S^b. \quad (2)$$

159

160 If the relationship between the proportion of sapwood area at the crown base  $\frac{A_S}{A_B}$   
161 (dimensionless) and  $A_B$  (cm<sup>2</sup>) satisfies the following scaling relation,

162

163 
$$\frac{A_S}{A_B} = eA_B^f, \quad (3)$$

164

165 then the relationship between  $m_L$  (kg) and  $A_B$  (cm<sup>2</sup>) is derived as

166

167 
$$m_L = ae^b A_B^{(1+f)b}. \quad (4)$$

168

169 Therefore, the scaling exponent of  $m_L-D_B^2$  allometry is controlled by the values of coefficients  $b$   
 170 and  $f$  in Eqs. (2) and (3).

171 Specifically, if  $f=0$  means that sapwood fraction remains constant across sizes in Eq. (2),  
 172 then the  $m_L-A_B$  allometry in Eq. (5) is simplified as the following scaling equation with the  
 173 exponent of  $b$ :

174

175 
$$m_L = ae^b A_B^b. \quad (5)$$

176

177 Therefore, the scaling exponent of Eq. (5) is determined by the scaling exponent of  $m_L-A_S$   
 178 allometry of Eq. (2) in the special case  $f=0$ . If the scaling exponent of  $m_L-A_S$  allometry (Eq. 2) is  
 179 larger than unity, the scaling exponent of  $m_L-A_B$  allometry (Eq. 4 or 5) is larger than unity.

180 The case when the scaling exponent of  $m_L-D_B^2$  allometry becomes unity is generally  $b =$   
 181  $\frac{1}{1+f}$  in Eq. (4). Therefore, Eq. (5) indicates that even if  $f=0$ , that does not necessarily mean only  
 182  $b=1$  or the proportionality of  $m_L$  and  $D_B^2$  from Eqs. (4). Equation (4) suggests that the leaf mass  
 183 per unit sapwood area at the crown base  $m_L/A_S$  (kg cm<sup>-2</sup>) depends on the sapwood area  $A_S$  (cm<sup>2</sup>)  
 184 as follows:

185

186 
$$\frac{m_L}{A_S} = aA_S^{b-1} \quad (6)$$

187

188 If the number of conduits per unit sapwood area is assumed to be constant,  $m_L/A_S$  is regarded as  
 189 an index of conduit diameter. That is, the larger  $m_L/A_S$  is, the larger the conduit diameter is, and  
 190 vice versa. Based on Eq. (6), Eq. (1) corresponds to the case when the conduit diameter is

191 constant irrespective of tree size because the value of  $b$  is unity. In addition, the conduit diameter  
192 increases in larger trees compared to smaller trees if the value of  $b$  is greater than unity.

193

### 194 ***Regression analysis***

195 Bivariate relationships, i.e., the  $\frac{A_S}{A_B}-D_B^2$  (Eq. 3),  $m_L-A_S$  (Eq. 2), and  $m_L-D_B^2$  (Eq. 4) relationships,  
196 were analyzed using standardized major axis (SMA) regression (Warton et al. 2006) and  
197 ordinary least squares (OLS) regression, using the smatr package of R (v. 4.1.2, R Core  
198 Development Team, 2021). Significant differences among power (i.e., scaling) exponents were  
199 based on 95% confidence intervals (CIs).

200 In the present analysis, Inabu had 36 individuals whereas the other sites have six  
201 individuals on average (Table 1). Therefore, a mixed-effects linear regression model was  
202 performed in the  $m_L-D_B^2$  allometry (Eq. 4) to evaluate whether there is autocorrelation between  
203 data points from the same site, using the lmerTest package of R.

204

## 205 **Results**

### 206 ***Allometric scaling of leaf mass***

207 The allometric relationship between leaf mass ( $m_L$ ) and the square of the stem diameter at the  
208 crown base ( $D_B^2$ ) was approximated by a single regression line on log–log coordinates, applying  
209 to all stands (Fig. 2). The scaling exponent was 1.273 (95% CI, 1.179–1.375) in SMA and 1.226  
210 (95% CI, 1.128–1.324) in the OLS regression, both of which were significantly greater than  
211 unity. Performing a mixed-effects linear regression model, the scaling exponent was calculated  
212 to be 1.160 (95% CI, 1.006–1.314), which was significantly higher than unity, as with the SMA  
213 and OLS regression methods. Therefore, there is no profound autocorrelation between data  
214 points from the same site.

215

### 216 ***Allometry of leaf mass to sapwood area at the crown base***

217 The allometric relationship between leaf mass  $m_L$  and sapwood area at the crown base  $A_S$   
218 satisfied Eq. (2) for 12-year-old *C. obtusa* (Adu-Bredu and Hagihara 1996) (Fig. 3). The value of  
219 scaling exponent  $b$  is significantly higher than unity (1.448, 95% CI = 1.126–1.862) in the SMA



220 regression. Because the isometric relation between  $w_L$  and  $A_s$  given by Eq. (1) is not valid, the  
221 pipe model ratio at the crown base is not constant among trees. In contrast, the value of  $b$  is not  
222 significantly different from unity (1.337, 95% CI = 0.970–1.706) in the OLS regression. This  
223 method (OLS) at least covers isometry for the allometry of leaf mass to sapwood area at the  
224 crown base.

225

### 226 ***Relationship between the proportion of sapwood area at the crown base and the square of the*** 227 ***stem diameter at the crown base***

228 In a *C. obtusa* plantation, 12-year-old trees (Adu-Bredu and Hagihara 1996) had a negative  
229 correlation between the proportion of sapwood area  $\frac{A_s}{A_B}$  at the crown base and tree size  $D_B^2$ , as  
230 given by Eq. (3) (Fig. 4). However, the  $p$ -value of the linear regression between the logarithm of  
231 these two terms is too high (0.892) in both the SMA and OLS regression methods. This indicates  
232 that the available data do not show that the scaling exponent is significantly different from 0.  
233 Therefore, the proportion of sapwood area at the crown base is independent of tree size, although  
234 the proportion of sapwood area varied vertically within the tree (Longuetaud et al. 2006).

235

## 236 **Discussion**

### 237 ***Allometric scaling relation of leaf mass***

238 The allometric scaling relationships of  $m_L$  to  $D_B^2$  (Fig. 2) suggest that the amount of foliage per  
239 tree should be most closely correlated with the sum of the cross-sectional areas of the living  
240 pipes supporting them, which in turn is thought to be well approximated by the cross-sectional  
241 area of the trunk at the crown base. These relationships support fundamental concepts related to  
242 active and disused pipes within the pipe model theory (Shinozaki et al. 1964a, b); therefore, the  
243 stem diameter at the crown base  $D_B$  can serve as an overall basis for foliage amount estimation in  
244 any stand, regardless of the tree age or habitat.

245 In the present study, a scaling model is used (Eq. 4) to explore the underlying causes of  
246 an exponent that might increase above a value of 2. According to studies of plant hydraulic  
247 adaptation (Savage et al. 2010; Olson et al. 2014, 2018, 2021; Kocillari et al. 2021), natural

248 selection operates on allometric scaling exponents between sapwood area and stem cross-  
249 sectional area (Eq. 2) and foliage mass and stem cross-sectional area at the crown base (Eq. 4).

250 Because the scaling exponent of  $m_L-D_B^2$  allometry is controlled by the  $f$  value of the  
251 coefficient in the case  $b=1$  in Eq. (4) or Eq. (1), the scaling exponent of Eq. (4) is unity because  
252 the value of  $f$  in Eq. (3) is regarded as zero (Fig. 4). Therefore, this case cannot be applied to the  
253 present result of  $m_L-D_B^2$  allometry (Fig. 2). We conclude that the pipe model ratio at the crown  
254 base is not constant irrespective of tree size, and varies among individual trees. In fact, the  
255 allometric scaling exponent between leaf mass  $w_L$  and sapwood area at the crown base  $A_s$  is  
256 significantly higher than unity in SMA regression (Fig. 2).

257 According to Shelburne et al. (1993) and Mäkelä and Albrektson (1992), the foliage area  
258 to sapwood area ratio is lower in suppressed trees than in dominant trees, indicating that the  
259 constant pipe model ratio given by Eq. (1) is not applicable to a wide range of tree sizes.  
260 Shinozaki et al. (1964b) stated that the proportionality of  $w_L$  to  $D_B^2$  tends to segregate canopy  
261 trees from suppressed trees with less foliage. In suppressed trees, the scaling exponent  $(1+f)b$  of  
262 the  $m_L-D_B^2$  relationship (Eq. 4) becomes greater than unity, resulting in a positive scaling with  
263 the specific pipe length  $L$  (m) (Shinozaki et al. 1963a), namely  $L \propto (D_B^2)^\xi$ , where  $\xi$  is a positive  
264 scaling exponent. Thus, it is reasonable that  $L$  is related to competition among forest trees and is  
265 used as an index of the degree of suppression (Ogawa 2015).

266 However, the present  $w_L-D_B^2$  allometry with a scaling exponent greater than unity can be  
267 explained based on the more general scaling relation given by Eq. (4) and the sapwood area  
268 proportion relation given by Eq. (3). If the value of  $f$  in Eq. (3) is zero because the correlation  
269 between the proportion of sapwood area  $\frac{A_s}{A_B}$  at the crown base and tree size  $D_B^2$  is not significant  
270 (Fig. 4), the value of the scaling exponent of  $m_L-D_B^2$  allometry equals the value of the scaling  
271 exponent of  $m_L-A_s$  allometry. Therefore, the scaling exponent of  $m_L-D_B^2$  allometry can be  
272 determined by factors such as the size dependency of the pipe model ratio (Eq. 4) and constancy  
273 of the sapwood area proportion (Eq. 3) at the crown base.

274

## 275 *Hydraulic architecture*

276 From the perspective of the hydraulic architecture of trees, Eq. (1) is based on the assumption  
277 that the basic pipe elements of the plant vascular system are cylindrical, i.e., the conduit diameter  
278 does not change axially. However, the main property of the hydraulic system of trees is to have  
279 tip–base widening of the conduits theoretically (West et al. 1999; Koçillari et al. 2021) and  
280 experimentally (Anfodillo et al. 2006; Petit and Anfodillo 2009; Savage et al. 2010; Olson et al.  
281 2014, 2018, 2021). Therefore, this universal, ineludible pattern is considered to have a profound  
282 effect on the relationship between foliage mass and stem diameter.

283 Based on SMA regression in Eq. (2), the conduit diameter is higher in larger trees than in  
284 smaller trees because the scaling exponent of  $b$  is greater than unity (Eq. 7). In contrast, the OLS  
285 regression in Eq. (2) indicates that the conduit diameter is constant irrespective of tree size  
286 because the value of  $b$  did not differ significantly from unity. However, considering the result of  
287 the scaling exponent between leaf mass and the square of stem diameter at the crown base (Fig.  
288 2), it is reasonable to consider that the diameter of conduits widens with tree size.

289 Shinozaki's pipe model theory (1964a, b) assumes that plants do not have heartwood, or  
290 wood that is not conducting water to the foliage above the crown base. In the present study, the  
291 proportion of sapwood area  $\frac{A_S}{A_B}$  is constant (or  $f=0$ ) irrespective of tree size (Eq. 3) and in turn  $\frac{A_S}{A_B}$   
292 did not affect the allometric scaling relation in Eq (4). In this case ( $f=0$  in Eq. 4), the allometric  
293 scaling of  $m_L-D_B^2$  is operated only by the scaling exponent of  $b$  in the allometry of leaf mass  $m_L$   
294 to sapwood area  $A_S$  (Eq. 2). Therefore, the assumption of Shinozaki's pipe model theory seems  
295 to apply to the case  $f=0$  in Eq. (4).

296

## 297 **Conclusions**

298 The present scaling model (Eq. 5) can cover an exceptional case in which Shinozaki's pipe  
299 model predictions (1964a, b) should not explain that leaf mass vs. stem diameter at the crown  
300 base has an exponent greater than 2. The scaling exponent  $f$  of sapwood area vs. stem diameter at  
301 the crown base has no effect on leaf mass vs. stem diameter at the crown base, while the scaling  
302 exponent  $b$  of leaf mass vs. sapwood area at the crown base affects leaf mass vs. stem diameter at  
303 the crown base. Because the value of  $b$  is higher than unity, the present scaling model predicts

304 that the diameter of conduits at the crown base widens with tree size, indicating tip–base  
305 widening of xylem conduits.

306

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311 University of Arizona, for their invaluable comments.

312

### 313 **Figure legends**

314 **Fig. 1** Diagram of the stratified clipping method (Monsi and Saeki 1953). In the practical  
315 experiment, the trees were stratified into several vertical strata defined at 0–0.3, 0.3–1.3, and  
316 subsequent 1.0 m intervals from ground level to the top of the crown.

317

318 **Fig. 2** Allometric scaling relationships between the total leaf mass  $m_L$  and the square of the stem  
319 diameter at the crown base  $D_B^2$  in 52 *Chamaecyparis obtusa* trees at four study sites. Circles,  
320 Nagoya; squares, Inabu; triangles, Hourai; crosses, Dando. The regression line in the diagram is  
321 the equation  $y = 0.0191x^{1.273}$  (scaling exponent 95% confidence interval [CI], 1.179–1.375;  $R^2 =$   
322 0.927;  $P < 0.001$ ) for the SMA regression method. The respective equations with the OLS  
323 regression method and linear mixed model are  $y = 0.0125x^{1.206}$  (scaling exponent 95% CI, 1.091–  
324 1.333;  $R^2 = 0.875$ ;  $P < 0.001$ ) and  $y = 0.0322x^{1.160}$  (scaling exponent 95% CI, 1.006–1.314;  $P <$   
325 0.001).

326

327 **Fig. 3** Allometry between the total leaf mass  $m_L$  and sapwood area at the crown base  $A_s$  in 12-  
328 year-old *C. obtusa* trees. The regression line in the diagram is an approximation of  $y =$   
329  $0.0218x^{1.448}$  (scaling exponent 95% CI, 1.126 – 1.448;  $R^2 = 0.854$ ;  $P < 0.001$ ) for SMA  
330 regression method. The equation with the OLS regression method is  $y = 0.0301x^{1.338}$  (scaling  
331 exponent 95% CI, 0.970–1.706;  $R^2 = 0.854$ ;  $P < 0.001$ ).

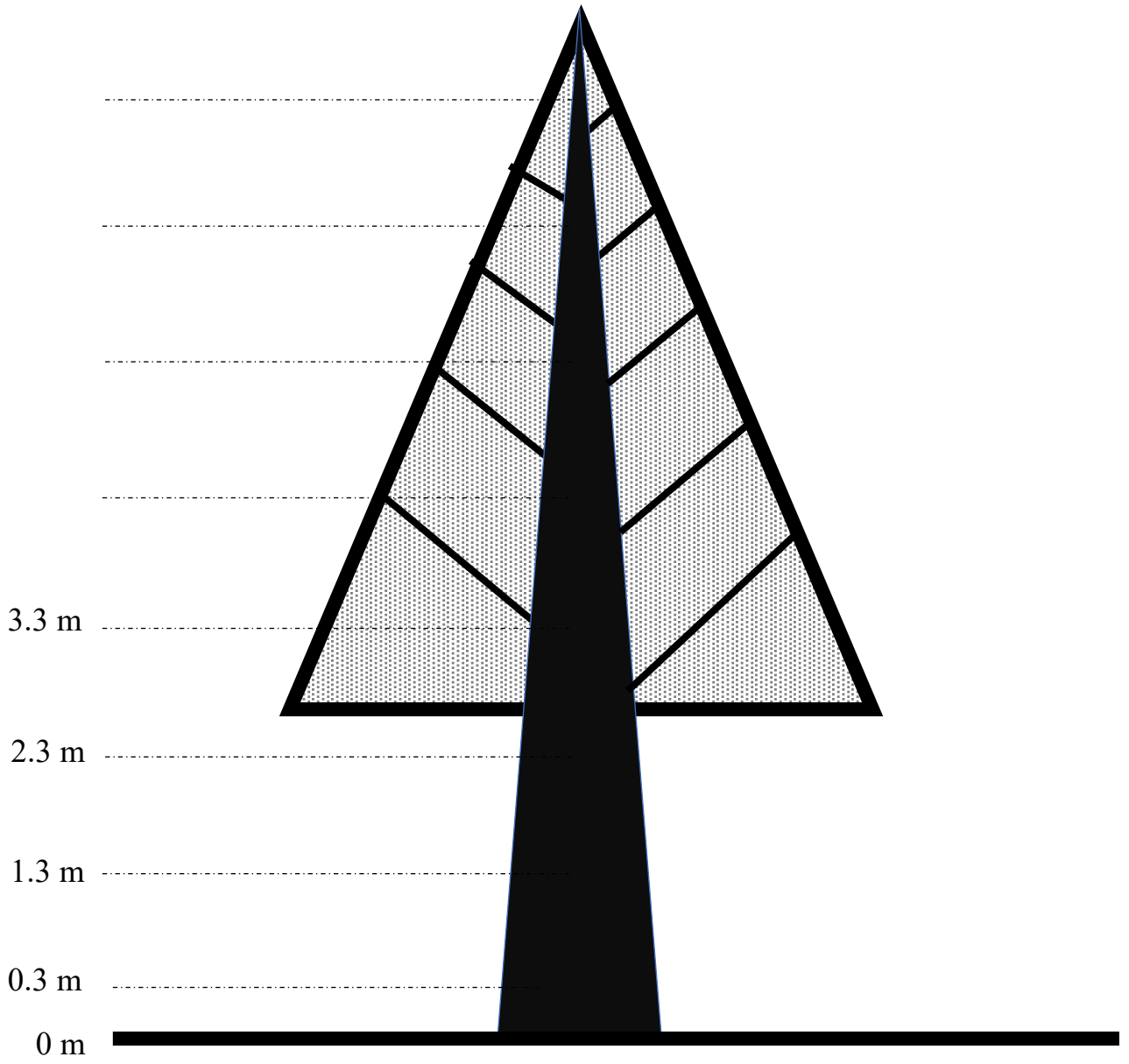
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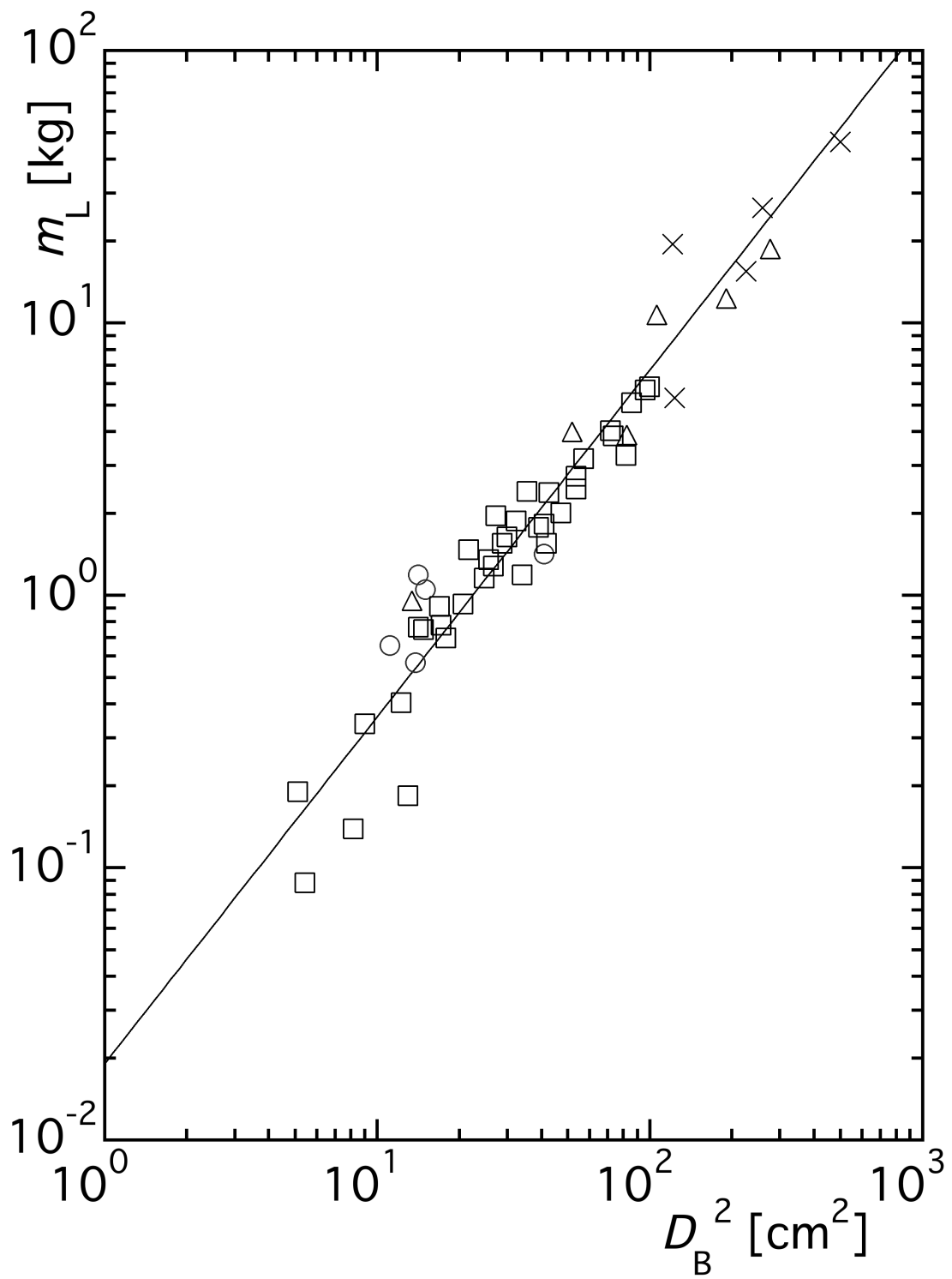
333 **Fig. 4** Relationship between the sapwood area proportion at the crown base  $\frac{A_S}{A_B}$  and the square of  
334 the stem diameter at the crown base  $D_B^2$  in 12-year-old *C. obtusa*. The regression line in the  
335 diagram is an approximation of  $y = 1.299x^{-0.173}$  ( $R^2 = 0.00176$ ;  $P = 0.892$ ) for the SMA  
336 regression method. The OLS regression equation is  $y = 0.723x^{-0.00727}$  (scaling exponent 95% CI, -  
337 0.122–0.108;  $R^2 = 0.00176$ ;  $P = 0.892$ )  
338

339 Fig. 1

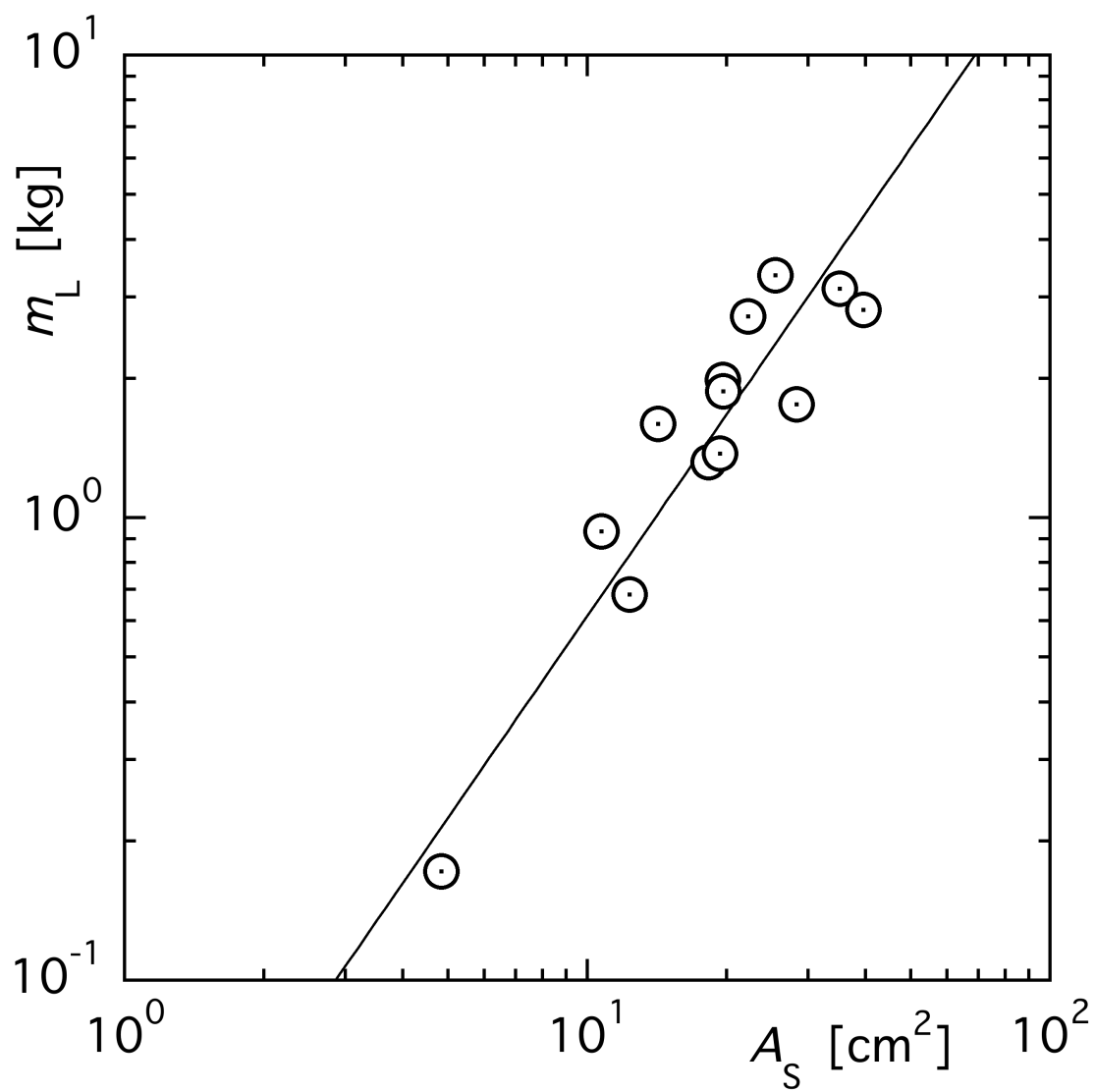
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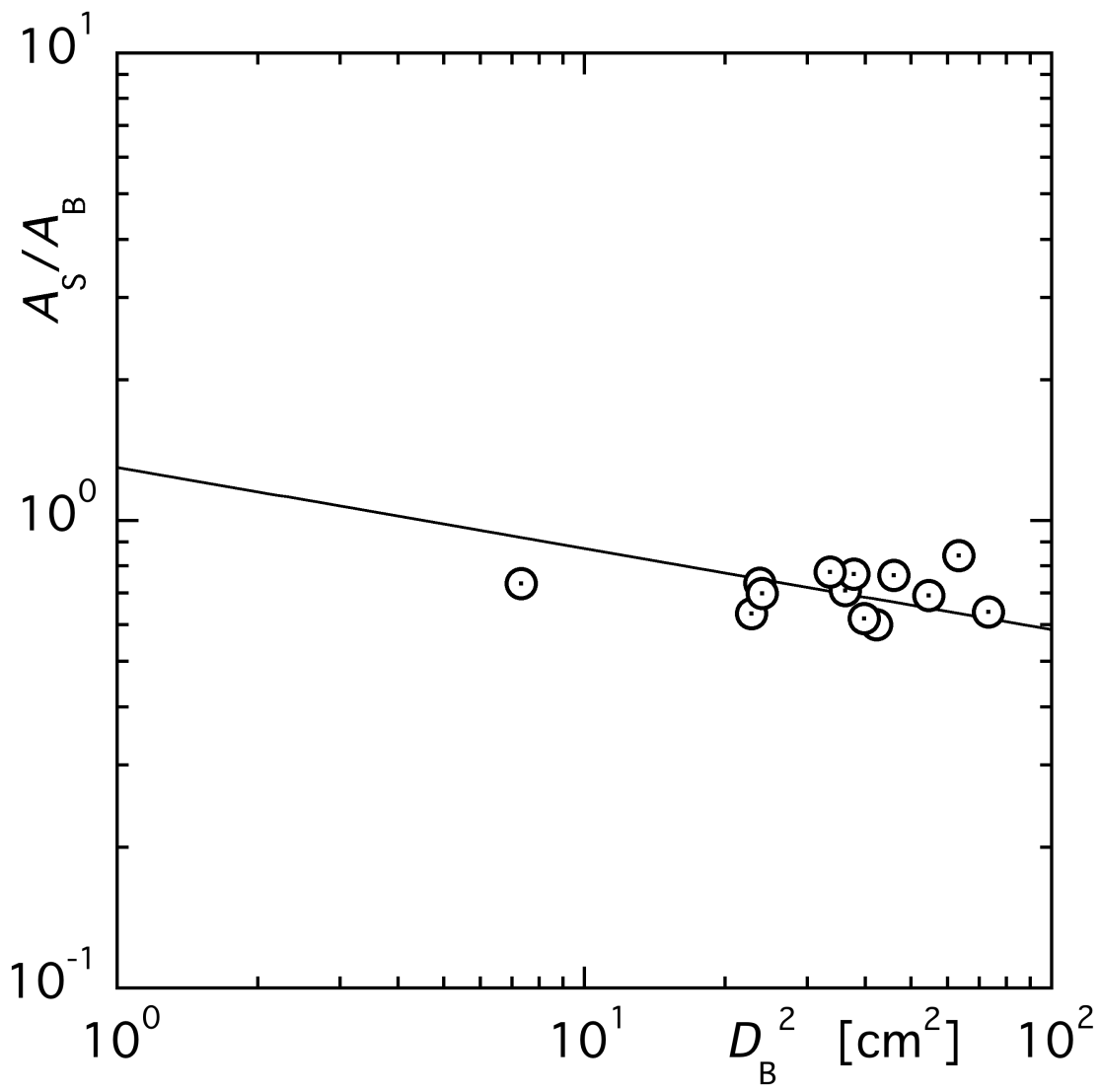


342  
343 Fig. 2  
344



345  
346 Fig. 3





347  
348 Fig. 4

Table 1. Summary of the trees used for sapwood area measurement (\$) and the allometric scaling relation (no symbols).							
Site	Age [yr]	Stand density [ $\text{ha}^{-1}$ ]	Tree height [m]	Crown base height [m]	DBH [cm]	$D_B$ [cm]	$n$
Nagoya\$	12	15000	3.3 – 5.7	n/a	2.90 – 8.28	2.71 – 8.56	13
Nagoya	12 – 16	15000	4.67 – 7.55	2.10 – 4.55	4.77 – 7.35	3.34 – 6.40	5
Inabu	16 – 25	6000 – 7500	4.73 – 12.1	1.25 – 6.00	3.47 – 13.4	2.26 – 9.99	36
Hourai	26 – 27	2281	7.92 – 12.2	5.06 – 5.90	8.02 – 23.1	3.66 – 16.6	6
Dando	58 – 59	2700	16.1 – 20.1	9.60 – 13.1	16.6 – 29.3	11.0 – 22.3	5
$D_B$ : stem diameter at crown base.							
$n$ : number of sample trees.							

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