OPEN ACCESS

Forest Systems 34 (2)
May-August, 2025, 20976
ISSN-L: 2171-5068, eISSN: 2171-9845
https://doi.org/10.5424/fs/2025342-20976

RESEARCH ARTICLE

Estimating crown biomass of three coniferous tree species using cross-sectional area at the base of live crown

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Abstract

Aim of study: The error in estimating branch biomass, foliage biomass, and crown biomass (i.e. sum of branch and foliage biomass) based on the diameter at the live crown base was evaluated.

Area of study: The foci were hinoki cypress [*Chamaecyparis obtusa* (Siebold et Zucc.) Endl.], Japanese larch (*Larix kaempferi* (Lamb.) Carrière), and Sakhalin fir [*Abies sachalinensis* (Fr.Schmidt) Mast.] in plantation forests located in Japan.

Material and methods: Nineteen cypress trees were destructively sampled in the four stands. Measurements from 64 cypress trees, 44 larch trees, and 27 fir trees were included in the analysis. A power function was applied as an allometric equation to establish the relationship between the diameter at the live crown base and the foliage, branch, and crown biomass. Cross-validation was performed to evaluate the precision and accuracy of biomass estimation for each component using the power function. Crown biomass was estimated from stem volume by using the basic wood density and the biomass expansion factor as a traditional method to compare the error.

Main results: Little bias was detected in the estimation of foliage, branch, or crown biomass. The percent root mean squared error was the lowest for branch biomass (36%, 26%), followed by crown biomass (52%, 26%) and foliage biomass (84%, 34%) for cypress and larch, respectively. These percent root mean squared errors were smaller than those using an allometric equation based on diameter at breast height and total height.

Research highlights: This study indicates the potential of using a single common allometric equation for each species to accurately estimate crown biomass.

Keywords: allometric equation, branch biomass, crown biomass, diameter at the base of the live crown, foliage biomass, hinoki cypress, Japanese larch.

Estimación de la biomasa de la copa de tres especies de coníferas mediante el área transversal en la base de la copa viva

Resumen

Objetivo del estudio: Se evaluó el error en la estimación de la biomasa de ramas, la biomasa del follaje y la biomasa de copa (es decir, la suma de la biomasa de ramas y follaje) basado en el diámetro en la base de la copa viva.

Área de estudio: Los focos fueron ciprés hinoki [*Chamaecyparis obtusa* (Siebold et Zucc.) Endl.], alerce japonés [*Larix kaempferi* (Lamb.) Carrière] y abeto de Sajalín [*Abies sachalinensis* (Fr. Schmidt) Mast.] en plantaciones forestales ubicadas en Japón.

Material y métodos: Se muestrearon diecinueve cipreses destructivamente en las cuatro masas. Se incluyeron en el análisis mediciones de 64 cipreses, 44 alerces y 27 abetos. Se aplicó una función de potencia como ecuación alométrica para establecer la relación entre el diámetro en la base de la copa viva y la biomasa del follaje, ramas y copa. Se realizó una validación cruzada para evaluar la precisión y exactitud de la estimación de la biomasa para cada componente utilizando la función de potencia. La biomasa de copa se estimó a partir del volumen del fuste utilizando la densidad básica de la madera y el factor de expansión de biomasa como método tradicional para comparar el error.

Resultados principales: Se detectó poco sesgo en la estimación de la biomasa de follaje, ramas y copa. El porcentaje de error cuadrático medio fue el más bajo para la biomasa de ramas (36%, 26%), seguido de la biomasa de copa (52%, 26%) y la biomasa de follaje (84%, 34%) para ciprés y alerce, respectivamente. Estos porcentajes de error cuadrático medio fueron menores que los obtenidos utilizando una ecuación alométrica basada en el diámetro a la altura del pecho y la altura total.

Aspectos destacados de la investigación: Este estudio indica el potencial de utilizar una única ecuación alométrica común para cada especie para estimar con precisión la biomasa de la copa.

Palabras clave: alerce japonés, biomasa de copa, biomasa del follaje, biomasa de ramas, ciprés hinoki, diámetro en la base de la copa viva, ecuación alométrica.

Citation: Tatsuhara, S (2025). Estimating crown biomass of three coniferous tree species using cross-sectional area at the base of live crown. Forest Systems, Volume 34, Issue 2, 20976. https://doi.org/10.5424/fs/2025342-20976

Received: 11/11/2024. Accepted: 31/03/2025. Published: 06/03/2026.

Introduction

Forest carbon stocks have received substantial attention as key indicators in mitigating climate change. In accurate estimations of forest carbon stocks, accounting not only for stem biomass but also for the biomass of other tree components, namely, branches, leaves, and roots, is essential (Kamei et al., 2024). In addition to stems, branches and leaves can be used as fuel for woody biomass power plants. Therefore, their biomass must be calculated as a resource. When managing forest data of individual trees based on the three-dimensional (3D) information of standing trees, if the biomass of branches and leaves can also be estimated for each individual tree, the accuracy of estimating forest carbon stocks and resource yields can increase. For example, for thinning standing trees, increased accuracy in the evaluation of the reduction in the forest's carbon stock and the biomass yield due to thinning.

Traditionally, standing trees are assessed by measuring the diameter at breast height (DBH) and tree height to calculate stem volume. Stem biomass can be determined relatively easily from stem volume, but estimating the biomass of branches, leaves, and roots is challenging. Therefore, the aboveground biomass for each standing tree has typically been estimated using an allometric equation based on DBH and tree height, even though it can be estimated by cutting a tree into small sections and weighing it (Kershaw et al., 2017). Alternatively, stem volume can be calculated using a volume equation or volume table derived from DBH and tree height. The aboveground biomass is then estimated by multiplying stem volume by the basic wood density and a biomass expansion factor (Verra, 2023). Belowground biomass is estimated from aboveground biomass by using the root-to-shoot ratio (Verra, 2023).

Allometry describes the relationship between the sizes of different parts and organs of a tree. Allometric equations, which express the correlation between two or more dimensions of a standing tree, are commonly used to estimate forest biomass. These equations are particularly valuable for estimating tree dimensions that are difficult to measure directly, such as leaf area and leaf biomass, based on easily measurable traits such as DBH (Tziaferidis et al., 2022). Shinozaki et al. (1964b) demonstrated that the allometric relationship between basal area and foliage or branch biomass varies by stand, and the allometric relationship between the stem cross-sectional area at the base of the live crown and the foliage or branch biomass remains constant and is not affected by stand factors in birch forests. In other words, the accuracy of estimating branch and foliage biomass can be increased by measuring the diameter at the base of the live crown by adopting a commonly used allometric equation for a specific species. However, because the base of the live crown is typically beyond human reach, measuring its diameter directly on standing trees is difficult, rendering the methodology impractical for widespread use. To avoid measuring its diameter directly, Sumida et al. (2009) applied a formula proposed by Ormerod (1973) to determine the upper diameter at any given height based on total height and DBH to estimate the cross-sectional area at the live crown base from total height, height to live crown base, and DBH, ultimately estimating leaf area for Erman's birch (*Betula ermanii* Cham.) trees. Inagaki et al. (2020) used a similar approach to estimate the foliage and branch biomass of sugi (*Cryptomeria japonica* D. Don.) trees.

Methods for measuring the size of standing trees using remotely sensed data can be broadly divided into those using terrestrial laser scanning (TLS) and those employing structure-from-motion (SfM) from forest images (Gao & Kan, 2022). TLS enables the measurement of 3D forest spaces using point cloud data (Liang et al., 2016) and has been used to measure DBH and tree height at sample sites in traditional forest inventories (Lovell et al., 2003). Furthermore, stems can be extracted from TLS point cloud data to calculate stem volumes (Yu et al., 2013). By contrast, Fernández-Sarría et al. (2022) generated 3D models from images captured by digital camera using SfM and calculated the dimensions of the stem and crown of walnut trees (*Juglans regia* L.). Similarly, Gao & Kan (2022) used SfM multi-view stereo to generate 3D models of standing trees from digital images and measured DBH. These advances in 3D forest measurement have enabled the assessment of standing tree dimensions and upper stem diameter, which had been difficult to measure in traditional forest inventories.

In this study, to demonstrate the potential of estimating crown biomass using remotely sensed data, the error in estimating branch biomass, foliage biomass, and crown biomass (i.e. the sum of branch and foliage biomass) from the diameter at the base of the live crown was evaluated. The focus was on hinoki cypress [*Chamaecyparis obtusa* (Siebold et Zucc.) Endl.], Japanese larch [*Larix kaempferi* (Lamb.) Carrière], and Sakhalin fir [*Abies sachalinensis* (Fr. Schmidt) Mast.] in plantation forests in Japan. First, newly acquired data were combined with existing data to develop allometric equations relating the diameter at the base of the live crown to each type of biomass. Next, using cross-validation, the precision and accuracy of biomass estimates based on the live crown diameter were assessed, applying the allometric equations derived from the measured values. Moreover, they were compared with those based on the DBH and height and based on the volume.

Material and methods

Study sites

The newly surveyed site was a hinoki cypress plantation in Zemanjo-cho, Okazaki City, Aichi Prefecture, southern part of central Honshu (34° 59' N, 137° 23' E). The altitude ranged between 600 and 620 m above sea level. The annual precipitation in the area is 2315.2 mm and the minimum temperature is 0.3 °C, the maximum temperature is 22.7 °C, and the average temperature is 11.3 °C (Japan Meteorological Agency, 2022). It belongs to the warm temperate deciduous forest zone. The soil in the site is dry brown forest soil (National Land Agency, 1974). Four stands, ranging from mature to old forests, were selected, and plots were established within these stands (Table 1). The DBH of all standing trees within the plots was measured. Five diameter classes were established, ensuring an equal number of trees in each class. One sample tree from each diameter class was selected, felled, and surveyed between December 2023 and March 2024.

The existing data used in this study were collected from several hinoki cypress plantation forests, namely, those of Nagoya University, Nagoya University Inabu Forest (now the Inabu Field, Field Science Education and Research Centre, Nagoya University), Aichi Prefectural Forest Research Institute (now the Aichi Prefectural Forest and Forestry Research Centre), Dando National Forest in Shinshiro District Forest Office (now the Aichi District Forest Office) (Hagihara et al., 1993), the University of Tokyo Chiba Forest, Chiba Prefecture (in January, 1989) (Tange & Murakawa, 1990) and Mt. Watamuki in Hino Town, Shiga Prefecture (in early November, 1968) (Yamakura et al., 1972; Falster et al., 2015) (Table 2). Other data were collected from several Japanese larch plantation forests in the National Forest of Ueda District Forest Office and Usuda District Forest Office (now both are the Toshin District Forest Office), Nagano Prefecture in high altitude area of central Honshu (Kyoto University et al., 1963; Falster et al., 2015) (Table 2). All data for larch were collected late in the growing season, from late July to early August in 1961. Additional data were collected from some Sakhalin fir plantation forest in the National Forest of Omu District Forest Office (now Nishi-monbetsu

Subdistrict Forest Office, Abashiri-seibu District Forest Office) in Hokkaido (in August, 1979) (Abe, 1981) and two plots in at Hitsujigaoka Experimental Forest of Hokkaido Branch, Forestry and Forest Products Research Institute in Sapporo, Hokkaido (in autumn, 1998) (Osawa et al., 2005).

Table 1. Main attribute of sample plots and trees destructively sampled on the plots.

Plot				Trees destructively sampled		
Name	**Stand Age [1] (years)**	**Density (stems/ha)**	**Mean DBH (cm)**	**Number of trees**	**Mean DBH (cm)**	**Mean total height (m)**
Zemanjo A	48	1200	23.9	5	22.3	19.3
Zemanjo B	36	1300	23.1	5	22.6	18.5
Zemanjo C	95	1083	28.1	5	26.1	21.2
Zemanjo D	51	900	24.7	4	22.4	19.9

[1] For stand ages of plots A, B, and D, values shown are from forest inventory data. For plot C, because stand age in forest inventory data clearly differed from number of tree rings in the disc at 0.0 m aboveground, the value shown is the maximum number of tree rings in the disc at 0.0 m aboveground minus 3 years. No samples were collected from the largest DBH class in plot D because cutting down standing trees in that DBH class was dangerous; Table S1 shows attributes of all the trees destructively sampled.

Table 2. Main attributes of each study site in existing data published in the references.

Species	Site	Age [1] (years)	Density (stems/ha)	Number of trees sampled	Mean DBH [2] (cm)	Mean total height [2] (m)	Reference
Cypress	Nagoya	12–16	15000	5	5.5	6.2	Hagihara et al. (1993)
	Inabu A	16–20	6000–7500	18	6.5	6.6	
	Inabu B	22–25		5	7.8	8.2	
	Inabu C	24		6	7.3	8.0	
	Inabu D	25		8	7.7	8.6	
	Horai	26–27	2281	6	15.1	10.3	
	Dando	58–59	2700	5	23.2	18.2	
	Watamuki	30	3500	6	12.5	10.5	Yamakura et al. (1972), Falster et al. (2015)
	Chiba	87	1282	5	23.6	16.8	Tange & Murakawa (1990)
Larch	Usuda A	9	2294	5	6.6	6.0	Kyoto University et al. (1963), Falster et al. (2015)
	Daimon	10	2313	4	8.7	7.7	
	Wada	18	1400–1500	16	10.4	9.0	
	Usuda B	28	1033	8	13.0	13.1	
	Sugadaira	41	1088	6	18.2	18.5	
	Usuda C	48	376	4	23.0	19.7	
	Usuda D	56	190	1	35.9	26.7	

Species	Site	Age [1] (years)	Density (stems/ha)	Number of trees sampled	Mean DBH [2] (cm)	Mean total height [2] (m)	Reference
Fir	Omu	53	545	17	30.0	19.9	Abe (1981)
	Hitsujigaoka 8	26	3652	5	11.5	9.4	Osawa et al. (2005), Aizawa et al. (2012)
	Hitsujigaoka 9	26	3588	5	16.6	12.8	

[1] For age of sites Nagoya, Inabu A, Inabu B, Inabu C, Inabu D, Horai, Dando, values are sample trees' age. For sites Watamuki and Chiba and all larch sites, values are stand age. [2] Mean DBH and mean total height of trees destructively sampled.

Data collection

After felling the sample trees, tree height and the height to the base at the live crown base were measured using a tape measure. The two perpendicular diameters at the base of the live crown were measured by using a calliper. The tree was divided into strata at 0.0, 0.3 and 1.3 m aboveground and then at 1 m intervals above 1.3 m, separated into its stem, branches, and leaves. The green weights of stems, branches, and leaves by stratum, were measured in the field. Samples were collected from each stratum of branches and leaves, except when the total amount was small. Discs were cut at 0.0, 0.3 and 1.3 m aboveground and then at 2 m intervals beyond 1.3 m. If the remaining tree height was 3 m or less, a disc was collected from 1 m above that point to complete the disc collection. The samples of branches and leaves and discs were also weighed in the field to obtain their green weight.

The discs, that is stem samples, and branch and leaf samples were taken to the laboratory. The radius from the centre of each disc was measured in four directions, and twice the average value was used to determine the diameter at the disc collection height. The stem volume for each stratum was calculated based on this diameter, and the volumes from all strata were added to determine the total stem volume.

The discs were dried in a thermostatic oven at 105 °C for 96 h, and the branch and leaf samples were dried in the same oven at 95 °C for 48 h; their dry weights were measured immediately after drying (Saputro et al., 2003). For determining the dry weight of the stem, the ratio of the dry weight to the green weight of the discs was multiplied by the green weight of the stem in the corresponding stratum. For branches and leaves, the ratio of the dry weight to the green weight of the samples was similarly multiplied by the green weight of the branches and leaves in the corresponding stratum. The dry weights of the stems, branches, and leaves for each stratum were then summed to determine the stem, branch, and foliage biomass, respectively (Saputro et al., 2003) (Supplementary Table S1).

Data analysis

The following power function was applied as an allometric equation to model the relationship between the diameter at the base of the live crown (D_b) and foliage, branch, and crown biomass:

$$Biomass = a\,(D_b{}^2)^b \tag{1}$$

where a and b represent coefficients.

The function was preliminarily fitted to the data using ordinary non-linear least squares regression and heteroscedasticity was found in the residuals. Thus, equation (1) was fitted with generalised non-linear least squares regression, with the assumption that the variance of each observation yi was proportional to the 2θ-th power of the corresponding mean value $f(x_i)$ (Ritz & Streibig, 2008; Tatsuhara, 2012),

$$y_i = f(x_i) + \varepsilon_i\ ,\ \mathrm{var}\,(\varepsilon_i) = \sigma^2\,[f(x_i)]^{2\theta}. \tag{2}$$

Variance parameter θ was also estimated from the data. Additionally, the following power function used in many studies (Affleck, 2019; Menéndez-Miguélez et al., 2023) was applied as an allometric equation using DBH (D) and total height (H) as explanatory variables:

$$Biomass = a\,(D^2 \cdot H)^{b} \quad (3)$$

where a and b represent coefficients.

Equations (1) and (3) were fitted to the three components of biomass by species for the three species. The data used were both my measurements and the measurements from existing references for hinoki cypress, and the measurements from existing references for Japanese larch and Sakhalin fir (Table 3). The goodness of fit was evaluated using Akaike information criterion (AIC). Regression was performed using the 'gnls' function in 'nlme' package in R version 4.4.2 (R Core Team, 2024).

Table 3. Main attributes of trees destructively sampled on measured plots and on sites published in references.

Species	Attribute	Mean	Minimum	Maximum
Cypress (n = 82[1])	DBH (cm)	13.7	3.5	33.3
	Total height (m)	11.9	4.2	22.5
	D_b (cm)	9.5	2.3	22.3
	Foliage mass (kg)	5.92	0.09	46.3
	Branch mass (kg)	7.26	0.11	50.5
	Crown mass (kg)	13.18	0.19	96.80
	Volume (m^3)	0.174	0.003	1.047
Larch (n = 44)	DBH (cm)	13.1	4.0	35.9
	Total height (m)	11.9	4.3	26.7
	D_b (cm)	10.8	3.4	33.2
	Foliage mass (kg)	3.11	0.18	17.59
	Branch mass (kg)	10.43	0.44	97.28
	Crown mass (kg)	13.54	0.62	114.87
	Volume (m^3)	0.154	0.004	1.411
Fir (n = 27)	DBH (cm)	24.1	4.2	40.8
	Total height (m)	16.6	4.5	22.7
	D_b (cm)	17.7	4.6	31.3
	Foliage mass (kg)	17.60	0.20	52.00
	Branch mass (kg)	29.95	0.14	113.80
	Crown mass (kg)	47.55	0.34	163.00
	Volume (m^3)	0.490	0.004	1.292

[1] The number of trees sampled were 71 for volume of cypress. D_b, diameter at the base of the live crown.

Cross-validation was performed to evaluate the precision and accuracy of the biomass estimation of equations (1) and (3) for hinoki cypress and Japanese larch. For hinoki cypress, data were divided into 13 groups including four measured plots (Table 1) and nine sites published in the literature (Table 2), one per site. For each iteration, 12 sites of the 13 sites were used to develop the model, leaving one site excluded, and then the resulting equation was applied to the excluded one-site data to obtain the prediction errors. For Japanese larch, data published of the literature were divided into seven groups (Table 2), one per site. For each iteration, six sites in the seven sites were used to develop the model, leaving one site excluded, and then the resulting equation was applied to the excluded one-site data the same as hinoki cypress. Precision was evaluated by calculating the root mean squared error (RMSE) and percent RMSE (PRMSE) as precision indices by using equations (4) and (5), respectively. Accuracy was assessed by calculating the bias and percent bias by using equations (6) and (7), respectively.

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n}(y_i - \hat{y}_i)^2}{n}} \quad (4)$$

$$PRMSE = \frac{1}{\bar{y}}\sqrt{\frac{\sum_{i=1}^{n}(y_i - \hat{y}_i)^2}{n}} \quad (5)$$

$$Bias = \frac{\sum_{i=1}^{n}(y_i - \hat{y}_i)}{n} \quad (6)$$

$$Percent\ bias = \frac{1}{\bar{y}}\frac{\sum_{i=1}^{n}(y_i - \hat{y}_i)}{n} \quad (7)$$

The prediction errors were compared between the equations (1) and (3).

Additionally, crown biomass was estimated from stem volume (*v*) by using the basic wood density (*BWD*) and biomass expansion factor (*BEF*) as recommended for hinoki cypress and Japanese larch in Japan (Table 4) as follows:

$$Crown\ biomass = v \cdot BWD \cdot (BEF\text{-}1). \quad (8)$$

Table 4. Coefficients for estimations of living biomass for each species (Greenhouse Gas Inventory Office of Japan & Ministry of the Environment Japan, 2024)

Species	Biomass expansion factor		Basic wood density
	Stand age ≤ 20	Stand age > 20	(t-d.m. m^{-3})
Cypress	1.55	1.24	0.407
Larch	1.50	1.15	0.404

Data from 11 hinoki cypress sites, excluding two sites for which there were no measurements of the volume of sample trees, and from six Japanese larch sites, excluding one site for which there was only one sample tree, were used for this evaluation. The error of these estimates was calculated and compared with the estimates obtained from equation (1).

Furthermore, the coefficient *b* was fixed, and equation (1) was fitted to the data by site to determine coefficient *a* by site for biomass of all the component of Japanese larch trees, which were collected at the same season, and for branch biomass of hinoki cypress trees, which were not collected at the same season. A correlation analysis was performed between coefficient *a* and the forest age or density. The analysis was performed using the ‘cor.test’ function in R version 4.4.23.6.3 (R Core Team, 2024).

Results

As a result of fitting equations (1) and (3), the AIC was smaller in equation (1) in all cases, and the goodness of fit was better (Table 5). When the square of the diameter at the base of the live crown (D_b^2) was plotted on a double logarithmic scale against foliage, branch, and crown biomass, the data points were more concentrated on a regression line than when squared DBH times total height was plotted on the same scale against biomass of the three components (Fig. 1 and Fig. 2). The values of coefficient *b* in equation (1) were close to 1 for foliage biomass, larger than 1 for branch biomass, and between those for foliage and branch biomass.

Table 5. Coefficient values of the allometric equations for each biomass component.

Equation	Species	Component	*a* [1]	*b* [1]	AIC	Number of data
$a\,(D_b{}^2)^b$	Cypress	Foliage	0.0402	1.054	292.52	82
		Branch	0.0080	1.378	206.22	82
		Crown	0.0401	1.196	337.38	82
	Larch	Foliage	0.0241	0.992	68.83	44
		Branch	0.0301	1.163	151.01	44
		Crown	0.0503	1.120	174.76	44
	Fir	Foliage	0.0397	1.033	136.73	27
		Branch	0.0076	1.382	158.27	27
		Crown	0.0300	1.237	182.57	27
$a\,(D^2H)^b$	Cypress	Foliage	0.0312	0.653	328.36	82
		Branch	0.0040	0.899	239.07	82
		Crown	0.0253	0.763	390.00	82
	Larch	Foliage	0.0773	0.476	137.36	44
		Branch	0.0784	0.615	234.16	44
		Crown	0.1370	0.581	259.39	44
	Fir	Foliage	0.0157	0.748	149.09	27
		Branch	0.0026	0.983	179.62	27
		Crown	0.0105	0.889	203.60	27

[1] Values of the coefficients of $Biomass = a\,(D_b{}^2)^b$ or $Biomass = a\,(D^2H)^b$ fitted to the sample trees on measured plots and sites published in the literature; AIC, Akaike information criterion.

The cross-validation for equation (1) revealed that the absolute value of the percent bias was 6% for cypress foliage biomass, but was below 2.4% for the other components and species (Table 6). The PRMSE for hinoki cypress was the lowest for branch biomass at 36%, followed by crown biomass at 51% and foliage biomass at 84%, although that for Japanese larch was almost the same and was 26% for branch and crown biomass, followed by foliage biomass at 34% (Table 6). To show the expected errors when estimating biomass at each site using a single common allometric equation for each tree species, the errors at each site were observed. The error varied across study sites for hinoki cypress, with some sites showing higher errors than others. For hinoki cypress, the number of sites where the PRMSE was less than 40% was 10 for crown biomass, nine for branch biomass, and six for foliage biomass (Fig. 3a). The number of sites where the absolute value of the percent bias was less than 30% was 10 for crown biomass and branch biomass, and eight for foliage biomass (Fig. 3b). For Japanese larch, the number of sites where the PRMSE was more than 40% was one for biomass of all the three components (Fig. 3c). The number of sites where the absolute value of the percent bias was more than 30% was one for biomass of all the three components (Fig. 3d). Compared with equation (3), the absolute value of the percent bias for hinoki cypress has increased, but all other values have decreased.

The method of estimating branch and foliage biomass from stem volume by using basic wood density and biomass expansion factor had a percent bias of -38% and +6% and a PRMSE of 97% and 38%, for hinoki cypress and Japanese larch, respectively (Table 7). This method produced a large bias, and the allometric equation method was almost unbiased. The PRMSE for this method was approximately 1.5–1.76 times that for the allometric equation method. The bias and PRMSE were greater than those obtained using the allometric equation method.

For Japanese larch data, coefficient *b* was fixed, and equation (1) was fitted to the data by site to determine coefficient *a* by site. No relationship was found between coefficient *a* and either forest age or tree density (Fig. 4). The correlation analysis between the values of coefficient *a* and stand age or density showed that there was no significant correlation between coefficient *a* and stand age or density (Table 8).

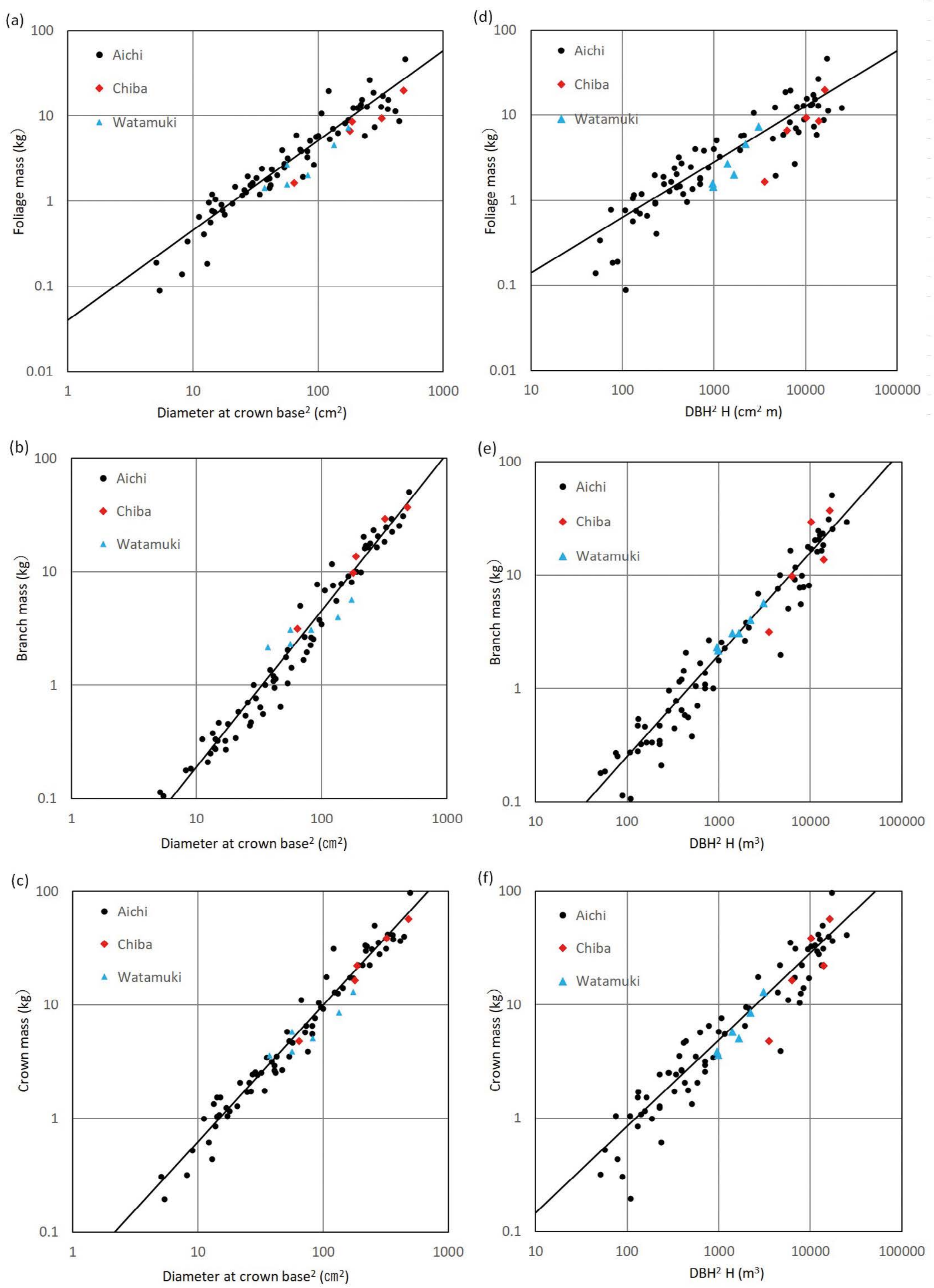

Figure 1. Relationships between squared diameter at base of live crown and (a) foliage biomass, (b) branch biomass, and (c) crown biomass for hinoki cypress and relationships between squared DBH multiplied by height and (d) foliage biomass, (e) branch biomass, and (f) crown biomass for hinoki cypress. Solid lines in all graphs represent the regression equation based on the overall data. Aichi includes all data except Chiba and Watamuki.

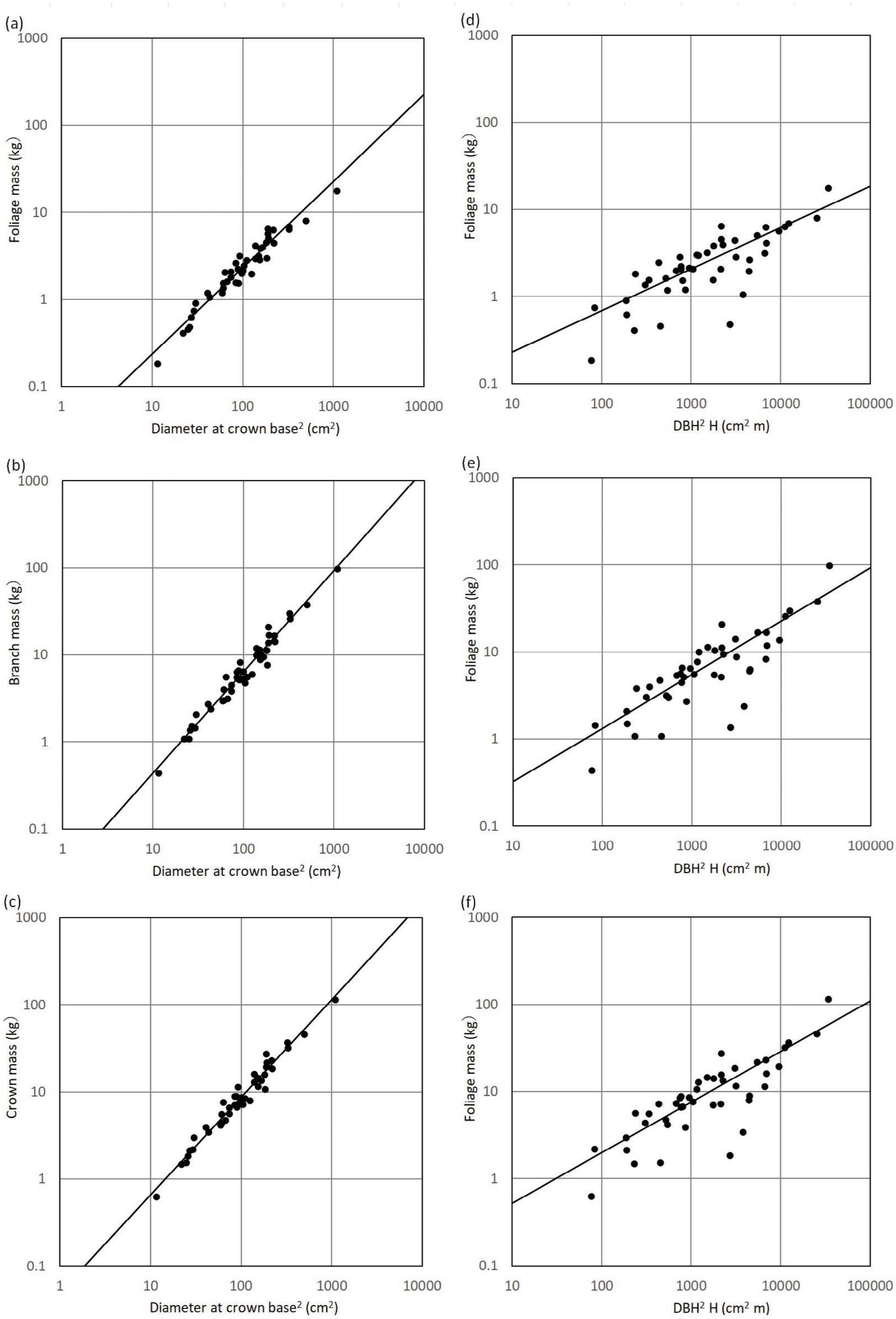

Figure 2. Relationships between squared diameter at base of live crown and (a) foliage biomass, (b) branch biomass, and (c) crown biomass and relationships between squared DBH multiplied by height and (d) foliage biomass, (e) branch biomass, and (f) crown biomass for Japanese larch. Solid lines in all graphs represent the regression equation based on the overall data.

Table 6. Comparison of estimation errors for each biomass component between two allometric equations.

Species	Tree component	Number of data	Average [1]	$a\,(D_b^2)^b$		$a\,(D^2 \cdot H)^b$	
				RMSE (PRMSE)	Bias (Percentage bias)	RMSE (PRMSE)	Bias (Percentage bias)
Cypress	Foliage	82	5.920	4.984 (84.2 %)	-0.3562 (-6.0%)	5.017 (84.8%)	-0.0998 (-1.7%)
	Branch	82	7.259	2.630 (36.2 %)	0.1746 (2.4 %)	3.821 (52.6%)	0.2988 (4.1%)
	Crown	82	13.18	6.801 (51.6%)	-0.1083 (-0.8 %)	7.900 (59.9%)	0.4887 (3.7%)
Larch	Foliage	43	2.776	0.9369 (33.8%)	-0.04472 (-1.6%)	1.210 (43.6%)	-0.2737 (-9.9%)
	Branch	43	8.409	2.167 (25.8%)	0.02408 (0.3%)	3.969 (47.2%)	-1.071 (-12.7%)
	Crown	43	11.19	2.864 (25.6%)	-0.04751 (-0.4%)	5.163 (46.2%)	-1.430 (-12.8%)

[1] Average biomass of each tree component; RMSE: root mean squared error; PRMSE: percentage root mean squared error

Table 7. Comparison of estimation errors for crown biomass between the two approaches.

Species	Approach	Number of data	Average [1]	RMSE (PRMSE)	Bias (Percentage bias)
Cypress	Equation (1)	71	12.71	7.120 (55.9 %)	0.3117 (2.5 %)
	BEF	71	12.71	12.33 (97.0%)	-4.833 (-38.0 %)
Larch	Equation (1)	43	11.19	2.864 (25.6%)	-0.04751 (-0.4%)
	BEF	43	11.19	4.297 (38.4%)	0.6493 (5.8%)

[1] Average biomass of each tree component; RMSE: root mean squared error; PRMSE: percentage root mean squared error; BEF: biomass expansion factor

Table 8. Correlation analysis between coefficient *a* in equation (1) and forest age or density.

		Foliage		Branch		Crown	
Species	Attribute	Correlation coefficient	*p*-value	Correlation coefficient	*p*-value	Correlation coefficient	*p*-value
Cypress	Stand age	-	-	0.384	0.218	-	-
	Density	-	-	-	-	-	-
Larch	Stand age	-0.561	0.246	0.548	0.261	0.428	0.397
	Density	0.693	0.127	-0.579	0.228	-0.422	0.405

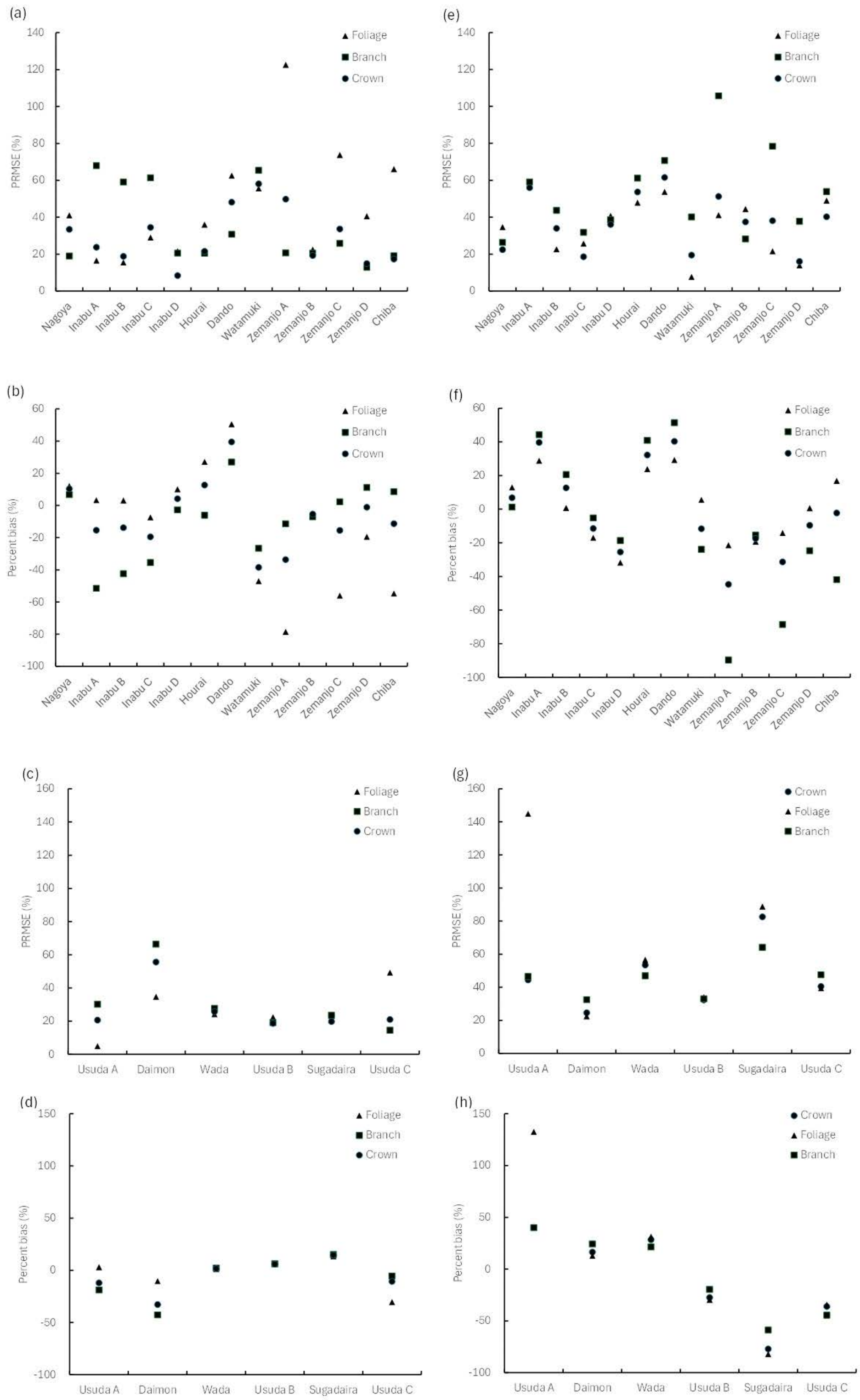

Figure 3. Percent root mean squared error (PRMSE) and percent bias in estimating branch, foliage, and crown biomass from squared diameter at base of live crown (a) and (b) for hinoki cypress and (c) and (d) for Japanese larch, and from squared DBH multiplied by height (e) and (f) for hinoki cypress and (g) and (h) for Japanese larch.

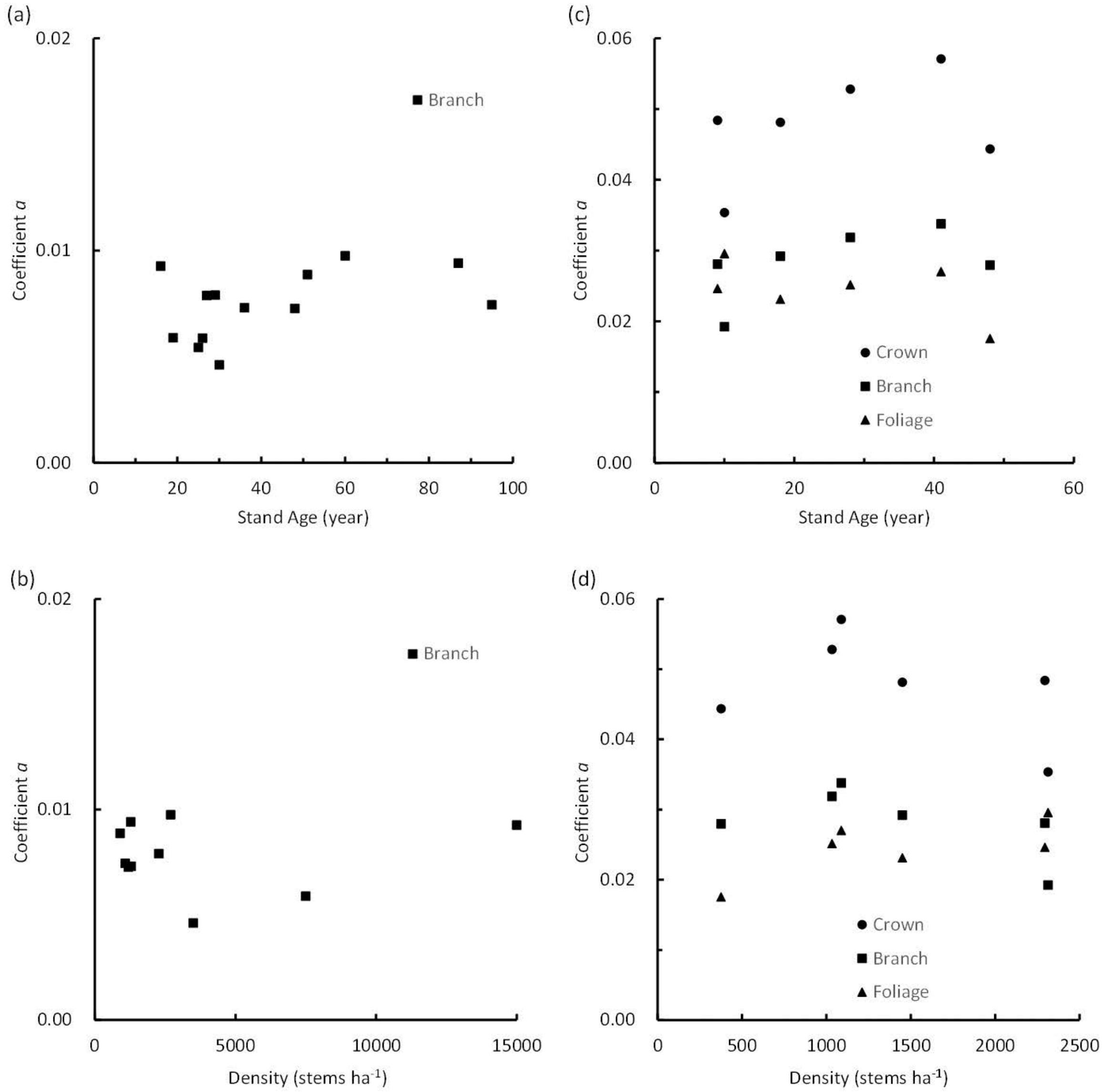

Figure 4. Relationship between coefficient *a* in equation (1) and (a) stand age or (b) density for hinoki cypress and (c) stand age or (d) density for Japanese larch. The Coefficient *a* was obtained by fitting equation (1) to data of each site, fixing the coefficient *b* for the species.

Discussion

The relationship between the square of the diameter at the base of the live crown and foliage or branch biomass was not clearly distinguishable between stands, unlike the relationship with the square of DBH times total height. In fact, the goodness of fit was better for equation (1) than for equation (3). Moreover, both precision and accuracy were much better than those achieved by the estimation method from stem volume and common basic wood density and biomass expansion factor to one species, and they were also better by the estimation method using the allometric equation from DBH and total height. According to the pipe model theory of tree form, foliage biomass is proportional to the total cross-sectional area of living pipes (Shinozaki et al., 1964a). Shinozaki et al. (1964b) demonstrated a similar relationship between the square of the diameter at the base of the live crown and branch biomass in a Japanese larch plantation forest. Amateis et al. (1992) also showed that the diameter at the base of the live crown was the most significant predictor variable for dormant-season foliage biomass of loblolly pine (*Pinus taeda* L.). Similar results to the above studies were obtained in the current study.

Dong et al. (2014) developed systems of biomass equations of tree components of three conifer species such as Korean spruce (*Picea koraiensis* Nakai), Korean pine (*Pinus koraiensis* Sieb. et Zucc.), and Dahurian larch (*Larix gmelinii* (Rupr.) Kuzen.) in northeastern China, and showed the mean prediction error (MPE) and mean absolute error (MAE) of prediction. The absolute values of MPE for all components were less than 3%, which meant that accuracy was good. In the three biomass components for Korean spruce and Dahurian larch, MAE was the lowest for crown biomass (7% and 19%), followed by branch biomass (14% and 32%), and was the highest for foliage biomass (21% and 54%). Korean pine had different tendency where all the three MAE were 33%, 38%, and 40% for branch, foliage and crown biomass, respectively. Affleck (2019) developed systems of biomass equations for aboveground components of seven conifer species in Northwest USA, and showed MAE of prediction. MAE for foliage biomass ranged from 25% to 40% and larger than those for live branch biomass and crown biomass ranging from 20% to 30%. MAE for live branch biomass was slightly larger than that for crown biomass. In the above studies, the precision tended to be smallest for crown biomass, followed by branch biomass and foliage biomass, in that order, which was consistent with this study. Although hinoki cypress leaves and branches were separated based on colour and thickness, accurately distinguishing those on the boundary was difficult. Leaves and branches in hinoki cypress cannot be clearly separated. This characteristic may have contributed to a high relative error rate for foliage biomass, which was less than branch biomass because the error in classifying leaves and branches is the same for foliage biomass and branch biomass. This problem can be overcome by combining foliage and branch biomass into a single crown biomass estimate when carbon stocks and resource yields in crowns are estimated. In this case, the time of calculations are reduced are the accuracy and precision are improved. On the other hand, this method is not applicable when biomass of the assimilatory organ and non-assimilatory organs of trees is required. When a component consists of two subcomponents, it is logical that its regression estimate is equal to the sum of the regression estimates of the two subcomponents (Parresol, 2001). In this case, regression should be performed taking additivity into account.

According to the pipe model theory of tree form, the power of the regression equation between the square of the diameter at the base of the live crown and foliage or branch biomass, namely, coefficient *b* in equation (1), is theoretically 1 (Shinozaki et al., 1964b). In this study, the value of coefficient *b* for foliage biomass in hinoki cypress plantations was close to 1, as expected. However, for branch biomass, the value of *b* exceeded 1, which led to a crown biomass value also a little greater than 1. Komiyama et al. (2002) reported similar findings in a mizunara oak (*Quercus crispula* Blume) mixed forest, a monarch birch (*Betula maximowicziana* Regel) mixed forest, and a Japanese blue beech (*Fagus japonica* Maxim.) forest. As the branches grow, the leaves closer to the stem fall off, leaving some lower branches with no leaves near the stem. Thus, as a tree grows, the ratio of branch biomass to foliage biomass tends to increase. This might be the cause of the difference in value for coefficient *b*.

Shinozaki et al. (1964b) pointed out that coefficient *a* varies slightly depending on the stand especially for shade intolerant species because branch shedding and the resulting accumulation of unused pipes in the trunks are naturally more obvious in shade intolerant species than in shade tolerant species, and demonstrated that coefficient *a* of small trees at unusually high densities (35,000–170,000 stems ha^{-1}) stands tended to be smaller than that of the dominant trees in mature stands, which was likely caused by a delayed response of lower branches to light deficiency. Tamai et al. (1983) demonstrated that coefficient *a* in equation (1) changed slightly between the ages 9 and 32 years, even within the same region, and that foliage and branch biomass for the same live crown diameter peaked at approximately 25 years of age. By contrast, for hinoki cypress plantation forests within a limited area of Aichi Prefecture, the relationship between the square of the live crown diameter and foliage or branch biomass was found to be linear on double logarithmic scales (Hagihara et al., 1993). Similar to the findings of Hagihara et al. (1993), it was observed that the square of the diameter at the base of the live crown and foliage or branch biomass was linearly related on double logarithmic scales in this study, especially for Japanese larch. However, comparing the sites in Aichi Prefecture with those from an 87-year-old hinoki cypress plantation forest in Chiba (Tange and Murakawa, 1990), it was found that the measurements for both regions aligned closely on double logarithmic scales (Fig. 1a, b, and c), with small estimation errors for branch biomass and crown biomass in Chiba (Fig. 3a and b) because PRMSE and percent bias were 19.1% and 8.5% for branch biomass and 17.4% and -11.3% for crown biomass, respectively. Despite the limited data, no significant differences were observed between Aichi and Chiba Prefectures. By contrast, results from a 30-year-old hinoki cypress plantation forest on Mt. Watamuki, Shiga Prefecture (Yamakura et al., 1972), showed the highest value for PRMSE and the second highest absolute value for percent bias in estimating crown biomass among the 13 study sites, with relatively high estimation errors for all the three components (Fig. 3) because PRMSE and percent bias were 55.6% and -47.1% for foliage biomass, 65.4% and -26.7% for branch biomass, and 58.1% and -38.5% for crown biomass. In the case of Japanese larch and hinoki cypress branch biomass in this study, no significant correlation was found between coefficient *a* and stand age or tree density. According to the pipe model theory of tree form, coefficient *a* may differ depending on stands, but this is likely to be due to differences in the way branches fall off during the growth process of stands.

The data were analysed by assuming that the allometric relationship between the stem cross-sectional area at the base of the live crown and foliage or branch biomass remains constant. However, foliage biomass changes slightly seasonally and annually. For example, Raison et al. (1992) demonstrated seasonal change in foliage biomass for *Pinus radiata* plantation. Sumida et al. (2018) showed that the leaf area index of individual hinoki cypress trees varied annually owing to residual effects of meteorological factors over the past 6 years. In this study, the data of Japanese larch were measured in the same season, which would also explain why the PRMSE of the species was much smaller than that of hinoki cypress. By contrast, the years and the seasons of data measurement for hinoki cypress varied. Therefore, even if there were subtle differences by year or season, they could not be clearly detected.

Conclusions

The relationship between the diameter at the base of the live crown and foliage, branch, and crown biomass for three coniferous species were analysed, demonstrating that crown biomass can potentially be estimated using a single common allometric equation with negligible errors. The errors were better than those achieved by the estimation method using the allometric equation with DBH and total height and by the estimation method from stem volume with basic wood density and biomass expansion factor. However, the error to estimate crown biomass using a single common allometric equation may be large depending on the stand. In particular, leaf biomass fluctuates seasonally and annually, so applying the allometric equation determined at one point in time to another point in time may result in large errors. Even if the biomass of a stand of the same tree species is estimated at the same point in time, the coefficient of this allometric equation vary depending on the way the branches die in the stand. Therefore, applying a single common allometric equation to stands with significantly different prescribed silvicultural regimes, such as stands in other regions or stands with extremely different densities from standard density, may result in large errors. Although there was a relatively large error for some individual trees, this method can likely be used to estimate the crown biomass of the entire forest stand. The focus of this study was only on plantation forests for three coniferous species, but similar analyses can be conducted for other tree species and other forest types, such as natural forests. To estimate canopy biomass with greater precision and accuracy, potential explanatory variables other than the diameter at the base of the live crown will be explored.

Supplementary material (Table S1): accompanies the paper on the *Forest Systems* website.

Data availability: The data that support the findings of this study are available from the corresponding author upon reasonable request.

Acknowledgements: This research was conducted as an industry-academia collaboration between DENSO Corporation and the University of Tokyo, with funding provided by DENSO Corporation. I thank Hirotsugu Kato from the Social Innovation Business Development Function Unit, Social Innovation Business Development Planning Department, DENSO Corporation for his assistance with field measurements, and Shoya Itakura from the Faculty of Agriculture, University of Tokyo, for his assistance with sample drying and weighing. I would like to thank Editage (www.editage.com) for English language editing.

Competing interests: The author has declared that no competing interests exist.

Statement about use of generative AI: The author employed Google Translate in order to translate original English title, abstract, and keywords into Spanish while preparing this work. Following their use, the author assumed full responsibility for the publication's content and reviewed and edited it as necessary.

Authors' contributions: Satoshi Tatsuhara: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Project administration, Resources, Validation, Visualization, Writing – original draft, Writing – review & editing.

Funding:

Funding agencies/institutions	Project/Grant
DENSO Corporation	industry–academia collaboration

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