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Comparison of models for estimating stem surface area of coniferous trees grown in old-growth natural forests

Akio Inoue [a], Ryota Koyama[a], Kazuki Koshikawa[b] and Kazukiyo Yamamoto[c]

aFaculty of Agriculture, Kindai University, Nara, Japan; bFaculty of Environmental and Symbiotic Sciences, Prefectural University of Kumamoto, Kumamoto, Japan; cGraduate School of Bioagricultural Sciences, Nagoya University, Nagoya, Japan

ABSTRACT

Stem surface area (S) plays an important role in the eco-physiological processes of trees or forests such as stem respiration, self-thinning mortality, and rainfall interception. As the direct measurement of S is time-consuming and labor-intensive, models for predicting S from commonly measured tree attributes have been developed for coniferous trees grown in plantations. However, there have been no models for trees grown in natural forests. In this study, we compared regression models for estimating S using 122 sample trees of eight coniferous species felled in old-growth natural forests in Kiso district, Nagano prefecture, central Japan. The relationship of S to the product of diameter at breast height and tree height (DH) could be expressed as $S = 1.924DH$ ($R^2 = 0.996$), independent of the species. The estimated slope coefficient of the regression of the natural forests was close to that of plantations reported in a previous study. These findings indicated the generality and wide applicability of the model. By contrast, the estimated slope coefficient of the regression between S and basal area (G) varied with the species, and the slope was gentler in the natural forests than the plantations. Monte Carlo simulation revealed that only 20 sample trees were necessary to estimate regression coefficient for the relationship between S and DH, whereas more than 60 trees were needed if G was used as predictor. In conclusion, the regression model between S and DH is useful when predicting S of various coniferous trees grown in both natural forests and plantations.

Introduction

The stem surface area (S) of trees or forests plays an important role in the eco-physiological processes such as stem respiration (Gavrikov 2015a; Katayama et al. 2019; Zhao et al. 2019), self-thinning mortality (Inoue and Nishizono 2015; Gavrikov 2014, 2015b), and rainfall interception (Iida et al. 2017; Jeong et al. 2020). The S has also been widely used as a measure of potential stem growth (Lexen 1943; Husch et al. 2003), and it represents a habitat for various insects (Borkowski and Podlaski 2011; Borkowski and Skrzecz 2016). Despite its importance, S has received less attention for the last half century (Swank and Schreuder 1974; Gavrikov 2017).

A direct measurement of S of standing trees is difficult (Inoue 2004). The most reliable measurement method is destructive sampling as follows: 1) The target tree is felled at ground level and all branches are cut from the stem; 2) The stem diameters are directly measured at a dozen points along the stem; and 3) S is calculated by the sectional measurement method (Inoue and Sakamoto 2017; Inoue et al. 2018) or the integration of stem taper equation (Inoue 2004, 2006). Such destructive sampling is, however, time-consuming and labor-intensive (Inoue et al. 2018). Destructive sampling also makes it impossible to examine the development of S with tree growth after the felling.

For these reasons, models that predict S from commonly measured tree attributes such as diameter at breast height (D), tree height (H) and basal area (G; calculated as $G = \pi D^2/4$) have been developed for coniferous tree species. The cone assumption model enables us to compute S from D (or diameter at base) and H geometrically by assuming that the stem form is a cone (e.g., Gavrikov 2014, 2015b; Katayama et al. 2019; Zhao et al. 2019). In contrast, several scientists

have proposed regression models for predicting S (e.g., Lexen 1943; Carron 1968; Swank and Schreuder 1974; Inoue 2004; Inoue et al. 2018). The relationship between S and the product of D and H for Pinus ponderosa could be expressed by the following regression equation:

$$S = \alpha DH \tag{1}$$

where α is the slope coefficient (Lexen 1943). Intraspecies variation in α was reasonably small for all sites and ages of Pinus radiata plantations (Carron 1968). No interspecies variation in α was also found between Cryptomeria japonica (L.f.) D. Don and Chamaecyparis obtusa (Sieb. et Zucc.) Endl. (Inoue 2004). Furthermore, the relationship between S and G could be represented as

$$S = \beta G \tag{2}$$

where β is the slope coefficient, which was significantly different between C. japonica and C. obtusa (Inoue 2004). It should be noted that these regression models were determined from sample trees collected from plantations. To our knowledge, there have been no models to estimate S of trees grown in natural forests. In Japan, the different models (i.e., volume equations) have been applied to estimate stem volume between natural forests and plantations (e.g., Forest Planning Division of Japan Forestry Agency 2004). Is there a difference in the model coefficients for estimating S between trees grown in natural forests and those grown in plantations? Answering this question is beneficial for exploring the eco-physiological processes of natural forests.

The purpose of this study was thus to compare the regression models for predicting S of coniferous trees grown in

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natural forests, i.e., the models of S to DH and G. First, S was calculated for 122 felled trees of eight coniferous species collected from old-growth natural forests in Kiso district, Nagano Prefecture, central Japan (Hara 1981). Using the data, the model coefficients of Equations (1) and (2) were then estimated and were compared with those obtained in the coniferous plantations (Inoue 2004). Finally, a Monte Carlo simulation technique was applied to derive the number of samples required when determining the regression models for coniferous trees grown in the natural forests.

Materials and methods

The data used in this study were collected between 1916 and 1978 from 52 old-growth natural forests in Kiso district, Nagano Prefecture, central Japan, to analyze the growth of the natural forests and make their management plan (Hara 1981). The data included 122 felled coniferous trees of eight species (*C. obtusa, Thujopsis dolabrata* Seib. et Zucc., *Chamaecyparis pisifera* (Sieb. et Zucc.) Endl., *Abies homolepis* Sieb. et Zucc., *Sciadopitys verticillata* (Thunb.) Sieb. et Zucc., *Tsuga diversifolia* (Maxim.) Mast., *Abies veitchii* Lindl. and *Picea jezoensis* Carr. var. *hondoensis* (Mayr.) Rehd.). The sample trees covered wide ranges of D (from 4.7 to 82.6 cm), H (from 4.2 to 38.0 m) and tree age (from 38 to 392 yr). The tree height (H) and diameters outside bark at base, breast height (D) and upper positions with 1- or 2-m intervals above the breast height were measured for all sample trees. A general description of sample trees is shown in Table 1.

First, S of each sample tree was computed using the sectional measurement method (Inoue and Sakamoto 2017; Inoue et al. 2018). Second, Equations (1) and (2) were fitted to the relationships of S to DH and G, respectively (Inoue 2004). The regression was performed not only for all sample trees together but also for three species, i.e., *C. obtusa, T. dolabrate* and *C. pisifera*, individually. Note that the species-specific regression model could not be determined for the other five species, since the number of samples of these species was one or two (Table 1). The differences in the estimated slope coefficients were examined between the three species using the indicator variable approach (e.g., Bates and Watts 1988; Inoue et al. 2017) as follows: According to this approach, Equation (1) could be written as

$$S = (\alpha_0 + \alpha_1 s_1 + \alpha_2 s_2)DH \qquad (3)$$

where α_0, α_1 and α_2 were parameters, and s_1 and s_2 were indicator variables that defined as follows:

C. obtusa: $s_1 = 1$, $s_2 = 0$
T. dolabrate: $s_1 = 0$, $s_2 = 1$
C. pisifera: $s_1 = 0$, $s_2 = 0$.

Equation (3) has the following null and alternative hypotheses:

H_0: $\alpha_1 = \alpha_2 = 0$

and

H_a: at least one parameter is not equal to zero.

Similarly, the difference in the coefficients of Equation (2) among the three species was also examined using same approach. To evaluate the goodness of fit of the models, the RMSE was calculated for each model. The estimated slope coefficients of Equations (1) and (2) for the natural forests were compared with those of plantations (Inoue 2004) by following Sokal and Rohlf (1995).

To evaluate how many sample trees are needed for determining the regression model, the change in the slope coefficient, i.e., α in Equation (1) and β in Equation (2), with sample size (N) was examined using the Monte Carlo simulation technique (c.f., Kumagai et al. 2005). The sample trees ($N = 2$–120) were randomly selected from the original data ($n = 122$) without replacement, and then the slope coefficient was estimated for each sample size. After repeating this simulation 100,000 times, the probability density function of the slope coefficient was obtained. The coefficient of variation (CV) was calculated from the average and the standard deviation of the probability density function. Finally, the change in CV with N was analyzed for each regression model. Hereafter, the CV in the slope coefficients of Equations (1) and (2) are denoted as CV_α and CV_β, respectively. All statistical analyses were performed using R version 4.0.3 (R Core Team 2020), and $P < 0.05$ was considered statistically significant.

Results and discussion

Regression model between *S* and *DH*

Figure 1 depicts the relationship between S and DH. There was a strongly positive correlation between S and DH ($R = 0.995$), and the estimated slope coefficient of α in Equation (1) for all sample trees was 1.924 ($R^2 = 0.996$; see Table 2). The estimated species-specific slope coefficient of α was 1.927 ($R^2 = 0.998$) for *C. obtusa*, 1.909 ($R^2 = 0.996$) for *T. dolabrate* and 1.903 ($R^2 = 0.996$) for *C. pisifera*. The indicator variable approach demonstrated that the parameters were not significantly different from zero, indicating that interspecies variation in α would be ignorable and the species-specific regression model between S and DH could be unnecessary. The 95% confidence intervals of the estimated slope coefficient for the natural forests (1.903, 1.944) included the slope coefficient of the plantations of

Table 1. General description of sample trees.

| Species	Number of trees	Tree height (m)*	DBH (cm)*	Tree age (yr)*
Chamaecyparis obtusa (Sieb. et Zucc.) Endl.	92	20.2 ± 5.9	34.1 ± 16.4	160 ± 91
Thujopsis dolabrata Seib. et Zucc.	13	11.0 ± 7.5	17.4 ± 16.3	117 ± 97
Chamaecyparis pisifera (Sieb. et Zucc.) Endl.	11	24.0 ± 10.1	35.3 ± 16.7	149 ± 82
Abies homolepis Sieb. et Zucc.	2	25.1 ± 1.7	41.1 ± 5.7	155 ± 40
Sciadopitys verticillata (Thunb.) Sieb. et Zucc.	1	24.8	31.4	257
Tsuga diversifolia (Maxim.) Mast.	1	23.4	38.5	238
Abies veitchii Lindl.	1	27.3	46.5	112
Picea jezoensis Carr. var. *hondoensis* (Mayr.) Rehd.	1	25.8	54.9	252
All species	122	19.9 ± 7.2	32.8 ± 16.9	156 ± 90

* Mean ± S.D.
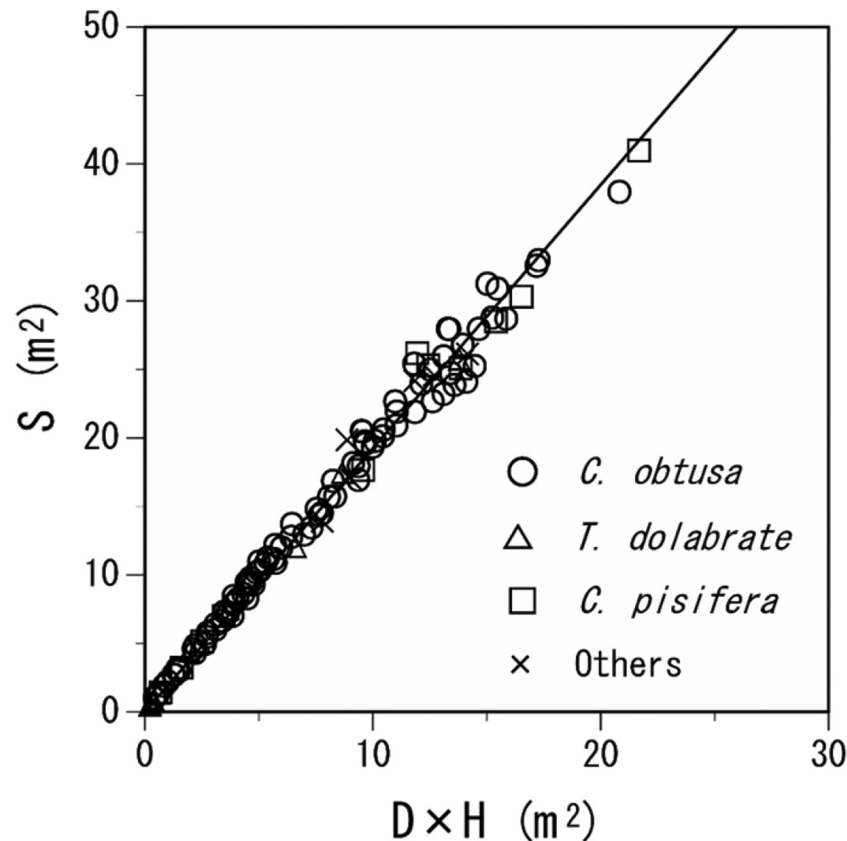
Figure 1. Relationship of stem surface area (*S*) to the product of diameter at breast height and tree height (*DH*). The solid line represents the following linear equation: $S = 1.924\ DH$ ($R^2 = 0.996$). The circles, triangles, squares and crosses indicate *Chamaecyparis obtusa* (Sieb. et Zucc.) Endl., *Thujopsis dolabrata* Seib. et Zucc., *Chamaecyparis pisifera* (Sieb. et Zucc.) Endl. and other five species, respectively.

Table 2. Statics of the regression models.

Model (Species)	Slope coefficient ± SE (95% CI)	r^2	RMSE (m^2)
$S = \alpha DH$			
Chamaecyparis obtusa (Sieb. et Zucc.) Endl.	1.927 ± 0.012 (1.903, 1.951)	0.996	1.021
Thujopsis dolabrata Seib. et Zucc.	1.909 ± 0.025 (1.854, 1.963)	0.998	0.438
Chamaecyparis pisifera (Sieb. et Zucc.) Endl.	1.903 ± 0.034 (1.827, 1.980)	0.996	1.304
All species	1.924 ± 0.010 (1.903, 1.944)	0.996	1.032
$S = \beta G$			
Chamaecyparis obtusa (Sieb. et Zucc.) Endl.	117.387 ± 3.659 (110.117, 124.657)	0.919	8.439
Thujopsis dolabrata Seib. et Zucc.	120.230 ± 4.870 (109.622, 130.844)	0.979	1.357
Chamaecyparis pisifera (Sieb. et Zucc.) Endl.	158.159 ± 6.403 (143.892, 172.426)	0.982	5.837
All species	122.853 ± 3.183 (116.551, 129.154)	0.925	7.609

C. japonica (1.937) and *C. obtusa* (1.921) in Okayama Prefecture, western Japan (Inoue 2004). For *C. obtusa*, it is noteworthy that the estimated slope coefficient of α for the natural forests (1.927) was close to that for the plantations (1.921). Furthermore, our data was collected from various sites (52 natural forests) and covered across wide ranges of stem sizes and tree ages (Table 1). Therefore, it is concluded that the regression model between *S* and *DH* could be generalized for coniferous trees, independent of the sites, species, stem sizes, tree ages and forest types (plantations or natural forests) in Japan.

Regression model between *S* and *G*

The relationship between *S* and *G* is shown in Figure 2. The *S* was significantly correlated with *G* ($R = 0.915$), and the estimated slope coefficient of β for all sample trees was 122.853 ($R^2 = 0.925$). However, the predictive performance of Equation (2) was inaccurate and imprecise for the natural forests: 1) The scatterplot of the relationship between *S* and

G varied widely; 2) The *S* was underestimated when *G* was less than 0.1 m^2; 3) The residuals increased as *G* became larger; and 4) RMSE was three to eight times larger in Equation (2) than Equation (1) (Table 2). The estimated species-specific slope coefficients of β for *C. obtusa*, *T. dolabrate* and *C. pisifera* were, respectively, 117.387 ($R^2 = 0.919$), 120.230 ($R^2 = 0.979$) and 158.159 ($R^2 = 0.982$). The indicator variable approach indicated the interspecies variation in the slope coefficient of β. The β of the plantation was 184.216 for *C. japonica* and 156.878 for *C. obtusa* (Inoue 2004), which were not included in the confidence intervals of the estimated slope coefficient for the natural forests (116.551, 129.154). Such variability in β reveals that the specific regression model between *S* and *G* is needed for each species and forest type.

The difference in the slope of α in Equation (1) is produced by the difference in stem tapering, whereas the difference in the slope of β in Equation. (2) is caused by the differences in stem slenderness and tapering (Inoue 2004; Inoue et al. 2018). The generality of the slope in Equation (1) as discussed above implies the small variation in the stem
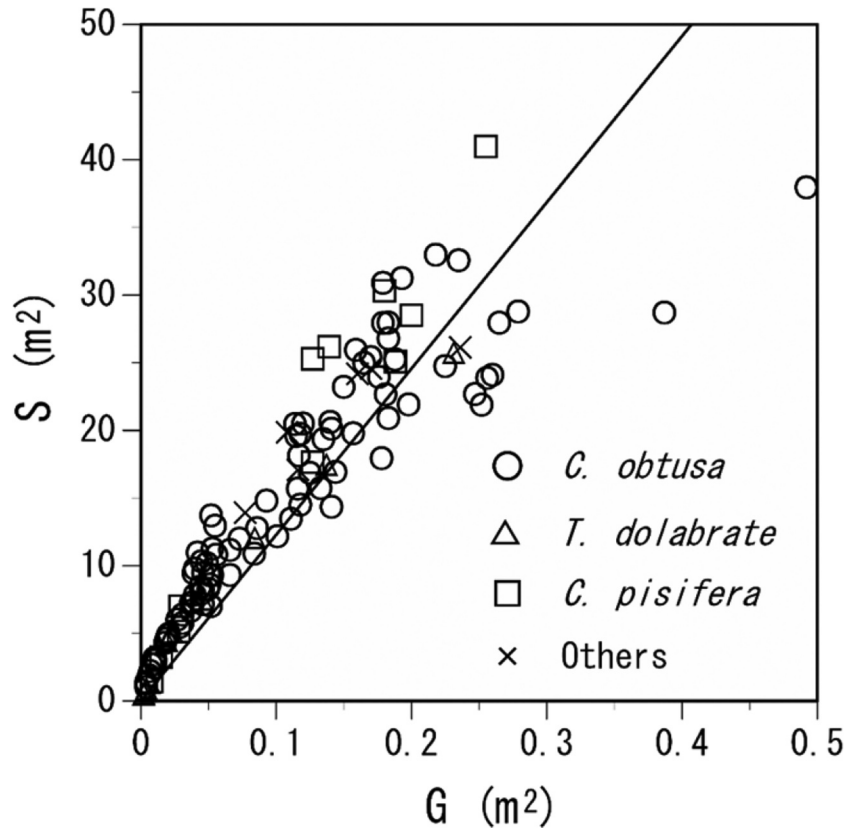
Figure 2. Relationship between stem surface area (*S*) and basal area (*G*). The solid line represents the following linear equation: $S = 122.853\,G$ ($R^2 = 0.925$). Legends are the same as in Figure 1
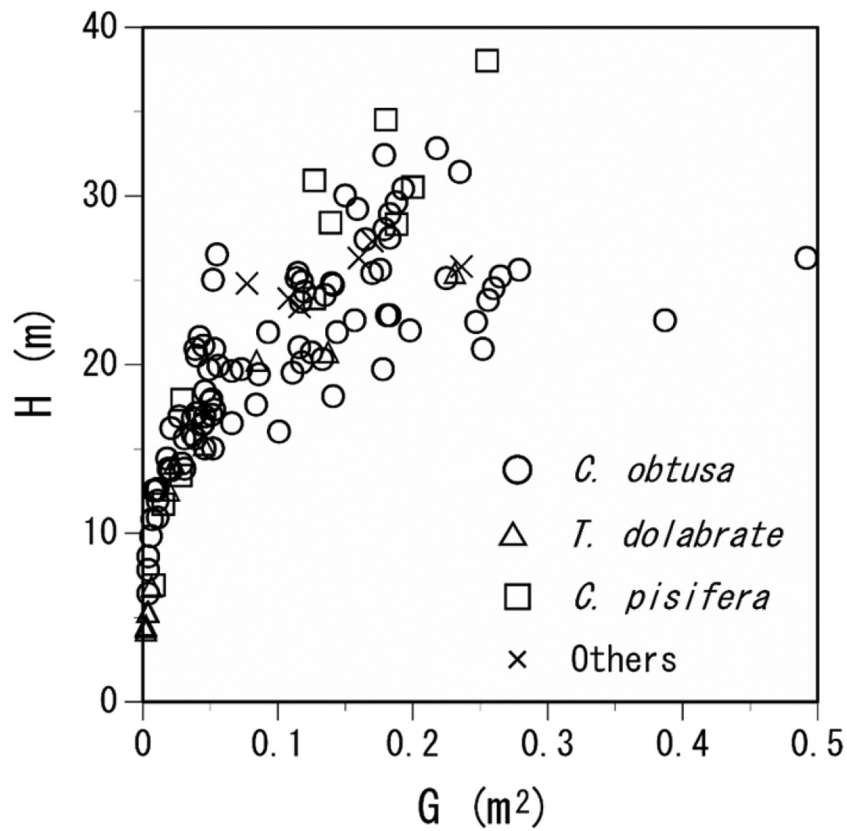

Figure 3. Relationship between tree height (*H*) and basal area (*G*). Legends are the same as in Figure 1.

tapering among the coniferous trees. Thus, the large variation in the relationship between *S* and *G* is caused by variation in stem slenderness, rather than variation in stem tapering. In fact, larger variation in the stem slenderness

(relationship between *G* and *H*) was found in our samples (see Figure 3). The variation in the stem slenderness among individuals is the reason why the predictive performance of Equation (2) was inaccurate and imprecise for the natural
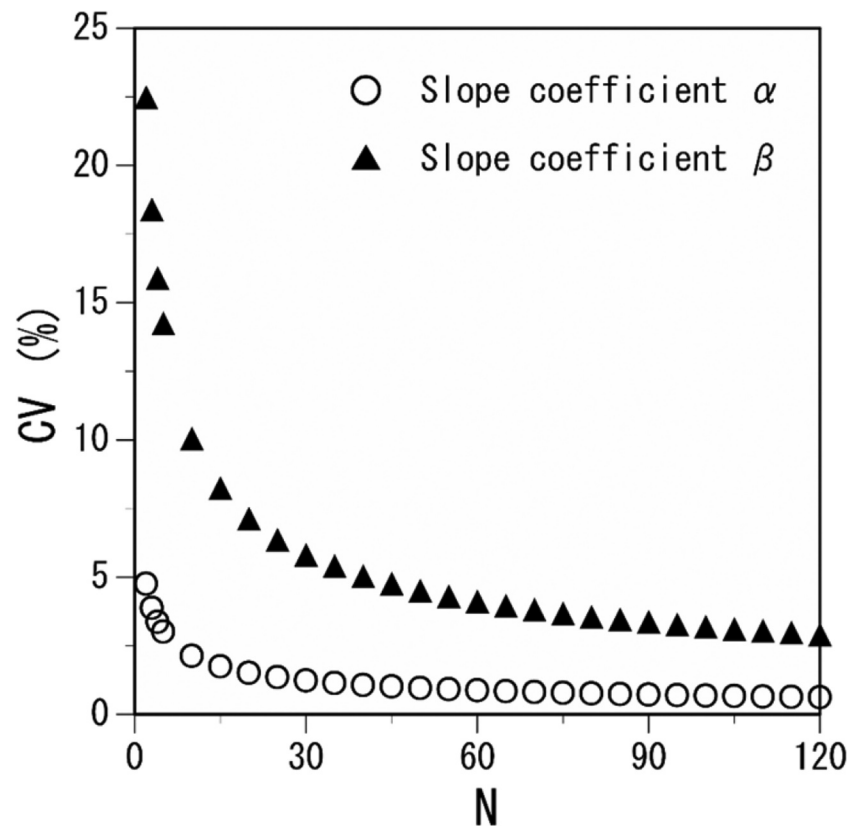
Figure 4. Changes in the coefficient of variation in the slope of the regression model (CV) with the number of sample trees (N). The circles indicate the slope coefficient of the regression α between stem surface area (S) and the product of diameter at breast height and tree height (DH), whereas the triangles represent the slope coefficient of the regression β between S and basal area (G).

forests. Therefore, the regression model between S and G, Equation (2), is inappropriate when predicting the S of trees grown in the natural forests, although the model enables us to estimate the S only from the measurement of D.

Sample size for determining the regression models

Figure 4 shows the change in CV of the slope (CV_α and CV_β) with N for each regression model based on the Monte Carlo simulation. For the regression model between S and DH, the CV_α gradually decreased from 4.75% when $N = 2$ to 0.61% when $N = 120$, with increasing N. When $N > 20$, the change in CV_α with N (dCV_α/dN) became less than 0.05% and the CV_α was almost stable, indicating that only 20 sample trees are needed when determining the regression model between S and DH for the coniferous trees grown in the natural forests.

The CV_β of the regression slope between S and G decreased rapidly with increasing N. The dCV/dN was less than 0.05% when $N > 60$, suggesting that at least 60 sample trees are necessary when determining the regression model between S and G for the natural forests. The CV_β was 4.10% when $N = 60$, which was almost equal to the CV_α when $N = 3$ (3.86%). If the comparable CV in the regression slope is required, the number of sample trees is considerably larger for the model between S and G compared to the model between S and DH. From this viewpoint, the regression model between S and DH is superior to the model between S and G.

Conclusions

In this paper, we compared two regression models for estimating S of coniferous trees grown in old-growth natural forests.

The estimated slope coefficient of the regression model between S and DH was independent of species and was close to that of plantations reported in a previous study (Inoue 2004). This implies that the regression model between S and DH could be generalized for various sites, species, stem sizes, tree ages and stand types (plantations or natural forests). In addition, the slope coefficient of the regression model can be determined only from 20 sample trees. On the other hand, the regression model between S and G was inappropriate for estimating the S. In conclusion, the regression model between S and DH presented here is useful when predicting the S of various coniferous trees grown in both natural forests and plantations, and beneficial for exploring the eco-physiological processes of the coniferous natural forests. In future, the model should be verified using other data sets of different species and countries.

Disclosure statement

No potential conflict of interest was reported by the authors.

ORCID

Akio Inoue http://orcid.org/0000-0002-0184-186X

References

Bates DM, Watts DG. 1988. Nonlinear regression analysis and its applications. New York: John Wiley and Sons.

Borkowski A, Podlaski R. 2011. Statistical evaluation of *Ips typographus* population density: a useful tool in protected areas and conservation-oriented forestry. Biodivers Conserv. 20:2933–2951.

Borkowski A, Skrzecz I. 2016. Ecological segregation of bark beetle (Coleoptera, Curculionidae, Scolytinae) infested Scots pine. Ecol Res. 31:135–144.

Carron LC. 1968. An outline of forest mensuration with special reference to Australia. Canberra: Australian National University Press.

Core Team R 2020. R: a language and environment for statistical computing. [accessed 2020 Oct 24. http://www.R-project.org/.

Forest Planning Division of Japan Forestry Agency. 2004. Volume tables for western Japan. Tokyo. Japanese: Japan Forestry Investigation Committee.

Gavrikov VL. 2014. A simple theory to link bole surface area, stem density and average tree dimensions in a forest stand. Eur J For Res. 133:1087–1094.

Gavrikov VL. 2015a. Whether respiration in trees can scale isometrically with bole surface area: a test of hypothesis. Ecol Model. 312:318–321.

Gavrikov VL. 2015b. An application of bole surface growth model: a transitional status of '−3/2′ rule. Eur J For Res. 134:715–724.

Gavrikov VL. 2017. Stem surface area in modeling of forest stands. Cham: Springer.

Hara T. 1981. A list of sample trees for stem analysis. Ann Rep Kiso Br For For Prod Res Inst. 22:16–25. Japanese.

Husch B, Beers TW, Kershaw JAJ. 2003. Forest mensuration. Hoboken: Wiley.

Iida S, Levia DF, Shimizu A, Shimizu T, Tamai K, Nobuhiro T, Kabeya N, Noguchi S, Sawano S, Araki M. 2017. Intrastorm scale rainfall interception dynamics in a mature coniferous forest stand. J Hydrol. 548:770–783.

Inoue A. 2004. Relationships of stem surface area to other stem dimensions for Japanese cedar (*Cryptomeria japonica* D. Don) and Japanese cypress (*Chamaecyparis obtusa* Endl.) trees. J For Res. 9:45–50.

Inoue A. 2006. A model for the relationship between form-factors for stem volume and those for stem surface area in coniferous species. J For Res. 11:289–294.

Inoue A, Miyazawa Y, Sato M, Shima H. 2018. Allometric equations for predicting culm surface area of three bamboo species (*Phyllostachys* spp.). Forests. 9:295.

Inoue A, Nishizono T. 2015. Conservation rule of stem surface area: a hypothesis. Eur J For Res. 134:599–608.

Inoue A, Sakamoto M. 2017. Comparing the methods for quantifying the culm surface area of bamboo, *Phyllostachys pubescens*. Ecol Res. 32:445–450.

Inoue A, Tochihara S, Sato M, Shima H. 2017. Universal node distribution in three bamboo species (*Phyllostachys* spp.). Trees. 31:1271–1278.

Jeong S, Otsuki S, Shinohara Y, Inoue A, Ichihashi R. 2020. Stemflow estimation models for Japanese cedar and cypress plantations using common forest inventory data. Agric For Meteorol. 290:107997.

Katayama A, Kume T, Ichihashi R, Nakagawa M. 2019. Vertical variation in wood CO_2 efflux is not uniformly related to height: measurement across various species and sizes of Bornean tropical rainforest trees. Tree Physiol. 39:1000–1008.

Kumagai T, Nagasawa H, Mabuchi T, Ohsaki S, Kubota K, Kogi K, Utsumi Y, Koga S, Otsuki K. 2005. Sources of error in estimating stand transpiration using allometric relationships between stem diameter and sapwood area for *Cryptomeria japonica* and *Chamaecyparis obtusa*. For Ecol Manage. 206:191–195.

Lexen B. 1943. Bole area as an expression of growing stock. J For. 41:883–885.

Sokal RR, Rohlf FJ. 1995. Biometry. New York: Freeman and Company.

Swank WT, Schreuder HT. 1974. Comparison of three methods of estimating surface area and biomass for a forest of young eastern white pine. For Sci. 20:91–100.

Zhao G, Liu G, Zhu W. 2019. Estimating individual- and stand-level stem CO_2 efflux in a subalpine forest: assessment of different extrapolation methods. Trees. 33:1603–1613.