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Stem volume and above ground biomass models for Sitka spruce (*Picea sitchensis* (Bong.) Carr.) in Iceland

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ABSTRACT

The prediction of tree biomass and stem volume is necessary for monitoring and assessing of national forest biomass, carbon stock and sustainable forest management. Such predictions of biomass or carbon stocks are generated by using either allometric models or applying biomass expansion factors (BEFs), where the former is a better method. Volume models are generated by using allometric models. The data for development of the new volume and biomass models for Iceland presented in this paper were collected between years 2000-2021, from 48 locations in even aged stands that were planted between 1942-1983. Because of the young age of forest plantations in Iceland, existing biomass and volume models need to be updated regularly as trees get older and larger. The new models use the same independent variables as the previous ones for Iceland but use a wider approach and have a different form than the older ones. Using the previous Icelandic models outside their data range results in underestimation for both aboveground biomass and stem volume.

Keywords: Biomass, stem volume, Sitka spruce, models

YFIRLIT

Bolrúmmáls- og lífmassaföll fyrir sitkagreni á Íslandi

Traust mat á lífmassa og bolrúmmáli trjáa er nauðsynlegt til vöktunar og mats á lífmassa og kolefnisforða í skógum á landsvísu og fyrir sjálfbæra skógarstjórnun. Slíkt mat á lífmassa eða kolefnisforða byggir annað hvort á því að nota lífmassaföll eða á því að beita lífmassastuðlum (BEFs) þar sem föllin eru nákvæmari aðferð. Þau gögn sem notuð voru við aðlögun nýrra rúmmáls- og lífmassafalla fyrir íslenskar aðstæður í þessari grein var safnað á árunum 2000-2021 og eru frá 48 stöðum víðsvegar um landið, úr jafnaldra skógum sem gróðursettir voru á árunum 1942-1983. Vegna þess að skógar á Íslandi eru ungir að árum, þarf reglulega að uppfæra föllin eftir því sem að tré eldast og verða stærri. Nýju föllin nota sömu breytur og eldri föll sem notuð hafa verið á Íslandi en hafa víðari nálgun og annað form en þau eldri. Notkun á eldri föllunum utan gagnasviðs þeirra leiðir til vanmats bæði á lífmassa ofanjarðar og bolrúmmáli.

INTRODUCTION

An accurate prediction of tree biomass and stem volume is essential for monitoring and assessing national forest biomass and for sustainable forest management. Information on tree biomass is required, among other reasons, to assess the amount of carbon (C) stored in trees and forests for reporting estimates of national carbon stock change to the United Nations Framework Convention on Climate Change (UNFCCC) and to fulfill the obligations of the Paris agreement (UNFCCC 1998). Information may also be needed to estimate the biomass and carbon removed from the forest in harvested logs and the amounts subsequently incorporated into wood products with different lifetimes (Romero et al. 2020). Volume models that estimate tree and stand volume have played a crucial role in forest inventories and management for more than a hundred years (cf. Jonson 1928, Näslund 1940, Laasasenaho 1982, Brandel 1990, Kangas et. al. 2022). Information on stem volume is also essential in sustainable forest management, which requires estimates of annual increment and growing stock. Such information guides forest managers in timber valuation as well as in allocation of forest areas for harvesting (Akindele & LeMay 2006).

Direct measurements of stem volume and biomass of living trees are laborious, costly, and therefore not a realistic alternative during routine inventories. The prediction of tree biomass is generated by using either allometric models or applying a biomass expansion factor (BEF). Volume prediction is generated by using allometric models. Biomass expansion factors are constants that convert stem volume or mass to whole tree biomass and may be developed into models by including relationships with age or tree size because of the typically strong relationship between BEFs and these variables (Lehtonen et al. 2004). Despite recent advances in remote sensing and other survey instruments, single tree allometric models are still fundamental to biomass and stem volume prediction and for calibrating emerging technologies and new approaches to earlier estimates (Asner & Mascaro 2014, Ferraz & Saatchi 2016). Because of the inherent morphological differences among and within tree species, it is generally necessary to develop separate standard biomass and volume models for each species or closely related species group that grow in each geographical area (Burkhart & Gregoire 1994).

Tree volume and biomass models at tree level are usually based on easily measurable variables. The models vary widely but diameter at breast height (DBH) is usually the most efficient single indicator of volume and biomass of trees (Husch et al. 1993). Single entry biomass and volume models that use only DBH as the independent variable are generally restricted to a local area, because trees in each diameter class can vary in height and form, especially those from different sites and densities of the stands. According to Philip (1994), volume and biomass models of this type must be restricted to a small range of diameters in a specific stand at a specific age. Other much used variables include measures of tree height (H), factors that affect tree form, such as age and living crown length, and independent stand level variables, such as stand density, altitude, site index, and latitude (Marklund 1988, Dutca et al. 2018, Brown 2002, Qichang et al. 2022). When the geographical range of the sample population is large, the divergent growth conditions may be reflected in more variation in the height to diameter ratio, so height, at least as a second independent variable, may be needed to lower the error of the model when making generic biomass or volume models (Marklund 1987, Wirth et al. 2004).

Iceland has proportionally the smallest woodland cover of Europe, merely 2% of total area, mostly remains of the native downy birch woodlands (*Betula pubescens*). Forest plantations presently cover 0.5% of the total area, or 45,000 ha (Keller et al. 2022).

Approximately 14% of the tree seedlings planted in the past century were Sitka spruce, *Picea sitchensis* (Bong) Carr., including the hybrid of Sitka spruce and white spruce, Lutzii spruce, *Picea x lutzii* (Pétursson 1999). In the current century, the importance of Sitka spruce has increased and its fraction in Icelandic afforestation has risen to 17%. Sitka spruce is the dominant species in approximately 15% of plantation forests, covering today around 6750 ha (Icelandic National Forest Inventory, unpublished).

The first biomass and volume models for Sitka spruce in Iceland were allometric models, developed and published by Snorrason and Einarsson (2006). However, because of the young age of forest plantations in Iceland, existing biomass and volume models need to be updated regularly as trees get older and larger. In this study, new models were developed and evaluated for estimating total aboveground biomass and total stem volume in Sitka spruce stands in Iceland, aiming to improve estimates of forest biomass and stem volume in Icelandic forests.

MATERIAL AND METHODS

In the present study, we evaluated empirical allometric models, partly on new data, to update relationships of total aboveground dry biomass and total tree volume. Data were collected from 48 locations in even-aged stands with destructive tree sampling during 2001-2021 (Figure 1). The data were from the Icelandic Forest Service research sites located in different parts of the country, planted between 1942 and 1983, and represented stands in different local climate regions, growing on different soil types, and covering most of the site conditions suitable for Sitka spruce-based forestry in Iceland.

The data for the development of the aboveground biomass and volume models originated from a different research project. The data consisted of tree-level measurements including diameter at breast height over bark (*DBH*, 1.3 m aboveground), total height (*H*) above stump, total stem volume (*V*) above stump and total aboveground biomass above stump (*BM*). The methods for data collection are detailed in the following paragraphs.

The data for developing the new total aboveground biomass models were from a research project dealing with the growth potential (Gpot) of different tree species planted in Iceland, described in Snorrason & Einarsson (2006). One tree was excluded from the earlier dataset of the Gpot project because of an obvious wrong registration in the field. Additionally, two new trees outside the range of the existing aboveground biomass models were sampled in 2021. The same sampling methodology was used there as in the earlier sampling (described in Snorrason and Einarsson 2006).

In the updated aboveground biomass models, Sitka spruce and white spruce data were combined after testing if they belonged to the same population. A species indicator (dummy) variable was added to the new allometric model and was not found to be significant, indicating that the species was not a relevant factor regarding biomass within the dataset. A total of 57 trees from 37 locations were used in updating the aboveground biomass models (Tables 1 and 2).

The data for the development of the stem volume models were from five different research projects and were collected during the years 2000-2021. A species indicator (dummy) variable was added to the new allometric model and was found to be significant, indicating that species was a relevant factor regarding stem volume prediction within the dataset. Thus, only the Sitka spruce data from the Gpot research project were used for the development of the new stem volume function.

From the Gpot dataset used in the development of the total aboveground biomass models, only the Sitka spruce data were used (30 trees). The rest of the Sitka spruce stem volume data were collected in provenance trials (PtH and PtS), thinning plots (TP) and permanent sample plots (PSP) for growth measurements within Iceland and were not used in the development of the older existing volume models. A total of 204 trees from 30 locations were used for updating the stem volume models (Tables 1 and 2).

For volume calculations, tree diameters over bark were measured at different relative heights on sample trees. From the Gpot data; every 5% of total height under breast height (1.3 m) and every 10% of total height over breast height were used. For TP and PSP, tree diameters over bark were measured at the following relative heights, which are given as percentages of the total tree height: 1, 2.5, 5, 7.5, 10, 15, 20, 30, 40, 50, 60, 70, 80, 90 and 95%. For PtH- and PtS data, diameters over bark were measured at the height of 0.5 m and then at one-meter intervals up to the top of the tree.

For each section, volume was calculated using Huber's formula, where the section is assumed to be a cylinder (Eqn. 1), and the top was treated as cone. The total stem volume over the stump was derived by adding all the volume sections together. Summary statistics and relevant tree characteristics are provided in Tables 1 and 2.

$$V = g_m L \qquad (1)$$

where V is volume of the log in dm^3, g_m is cross-sectional area at log midpoint in cm^2 and L is log length in m.

Table 1. Total number of sample trees used for biomass and volume models from different research projects. Gpot data are from a 2001 country-wide survey; PtH and PtS are data from provenance trials; TP data are from thinning plots; PSP data are from permanent sample plots. All the data are from the Icelandic Forest Service research sites located in different parts of the country.

	Gpot	PtH	PtS	TP	PSP	Total
Biomass function	57					57
Volume function	30	50	50	23	51	204

Table 2. Summary statistics for single tree attributes in the present study. *BM* is data for the total aboveground biomass models and *V* is data for the total stem volume models. *DBH* is diameter at 1.3 m above ground level and *H* is total height. S.D. is standard deviation.

Variable	Mean	S.D.	Maximum	Minimum
(*BM*) *DBH* (cm)	18.1	6.6	32.9	4.8
(*V*) *DBH* (cm)	15.1	6.7	36.0	2.8
(*BM*) *H* (m)	10.3	3.1	18.8	4.8
(*V*) *H* (m)	10.4	3.4	22.7	2.6
Total aboveground biomass (kg)	100.4	74.1	376.1	4.7
Stem volume (dm^3)	132.5	131.5	740.1	2.0

Multiple non-linear models evaluated in previous studies worldwide (Schumacher & Hall 1933, Spurr 1952, Clutter et al. 1983, Brandel 1990, Romero el. al. 2020) were tested in the present study to model the relationship

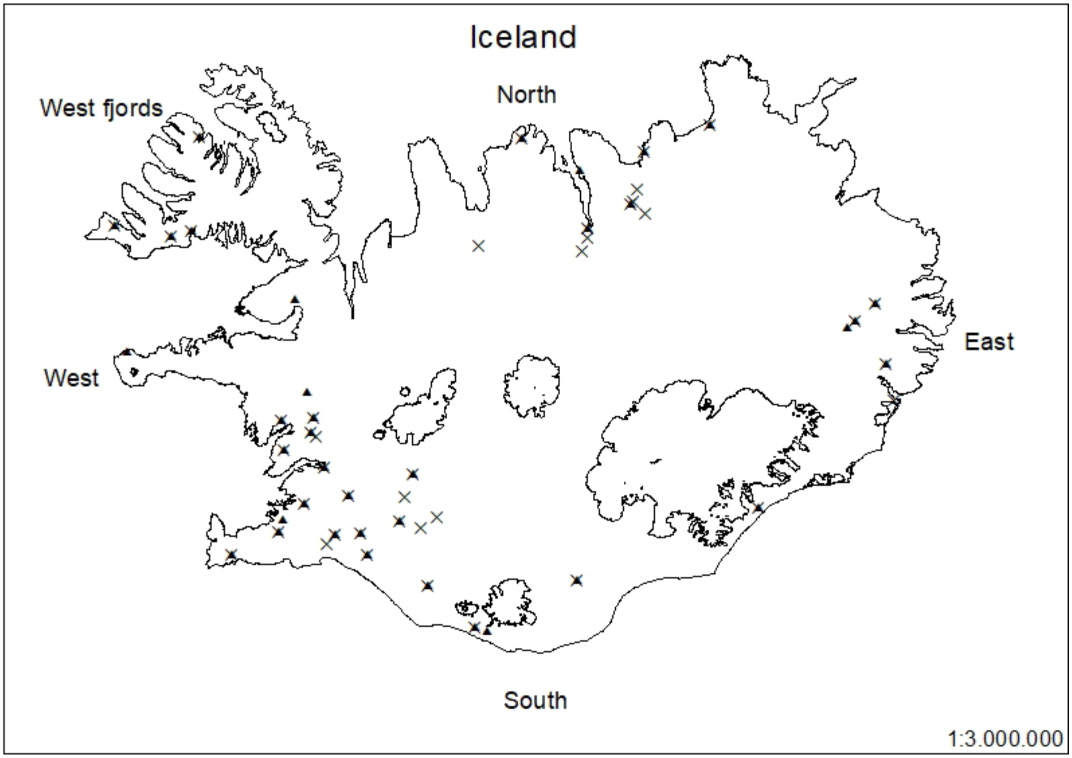

Figure 1. Location of the sample plots. Triangles = locations of plots for the biomass data and x = locations of plots for the volume data.

of total volume and total biomass with DBH, total height and different modifications of the variables. The final models selected to estimate the total aboveground biomass and total stem volume in this study were based on fit statistics and residual analyses and were:

$$BM_i = a \times DBH_i^b \times H_i^c + e_i \quad (2)$$

$$V_i = a \times DBH_i^b \times H_i^c + e_i \quad (3)$$

where BM_i is the total aboveground biomass in kg for tree *i*; V_i is the total stem volume in liters for tree *i*; DBH_i is diameter at breast height in cm for tree *i*; H_i is total tree height in m for tree *i; a, b* and *c* are parameters to be estimated; is the random error term of the function, which is assumed to be independent and identically distributed with mean equal to zero and constant variance.

To eliminate the bias effect of the error variance for volume and biomass models, which generally increases with tree size, and to reduce the effect of heteroscedasticity in the nonlinear models, the final model parameters were estimated with weighted nonlinear regression. The observations were weighted with the reciprocal of the prediction from a first unweighted model fit (Akindele & LeMay 2006).

A part of the dataset had a spatially hierarchical structure, i.e., several trees were measured from the same plot and trees from the same sample plot tend to resemble each other more than average. This hierarchical structure might result in dependence between observations within a certain plot or site. To check if there was dependence in the dataset, a mixed model approach was applied, where the stands and plots within stands were included as random effects (parameters) in the model. The mixed model approach didn´t reveal any effects of sites or plots in the model.

All the models tested were evaluated and compared based on bias (*B*) for systematic errors, standard error of estimate (*SEE*) as indication of precision, and the degree of explained variance (R^2). The weighted model residuals were also plotted against predicted volume to verify the assumption of equal variances. In the preliminary testing of the model selection the same statistics were used as in the final model selection. The estimated parameters for the new models were used to calculate fit statistics.

The statistics were defined as:

$$B = \frac{\Sigma(y_i - \hat{y_i})}{n} \quad (4)$$

$$SEE = \sqrt{\frac{\Sigma_{i=1}^{n}(y_i - \hat{y_i})^2}{n-1}} \quad (5)$$

$$R^2 = 1 - \left[\frac{\Sigma_{i=1}^{n}(y_i - \hat{y_i})^2}{\Sigma_{i=1}^{n}(y_i - \overline{y_i})^2}\right] \quad (6)$$

where y_i, $\hat{y}_i$ and $\bar{y}_i$ are the measured, predicted and average values of the dependent variable, and *n* is the total number of observations used to fit the model.

All regression analyses for both biomass and volume models were carried out with the SAS statistical software package version 9.2. The primary analysis of the volume function used the MIXED procedure, while further analysis of the volume and biomass models used the nonlinear regression NLIN procedure for parameter prediction and model fit. Figures and some statistics were made with R software, version 4.3.1 (Posit team 2023).

RESULTS

The parameter estimates and fit statistics for the weighted biomass and volume models are presented in Table 3. Both selected models had low overall bias and SEE (Table 3). The explained variance (R^2) for the updated total biomass model was slightly less (0.952) than in the previous study (0.965) by Snorrason and Einarson (2006). For the updated total volume model, the explained variance (0.992) was similar to the previous study (0.993) by Snorrason and Einarson (2006) (Table 3). This suggests that a large proportion of the variation in tree biomass and stem volume is explained by DBH and height. To better analyze the

Table 3. Parameter estimates and fit statistics of the weighted models for total biomass (2) and total stem volume (3). Bias, standard error of estimate (*SEE*) and explained variance (R^2). All estimated parameters are significant ($p < .001$).

Model	a	b	c	Bias	SEE	R^2
2	0.1128	1.7531	0.6634	0.004	16.5	0.952
3	0.0615	1.7612	1.0953	-0.07	11.91	0.992

performance of the models, the mean value of bias and SEE in different diameter classes were inspected and are shown in Table 4. The biomass model had a low bias in all diameter classes in comparison to the volume model but had a little higher bias in DBH classes over 20 cm. For both models the SEE increased with tree size and was at a similar magnitude for the biggest DBH class (Table 4).

In Figure 2 the fit of the new models is compared to measured values. The variation was slightly higher in the total biomass dataset compared to the total stem volume dataset. In Figure 3, the weighted residuals are plotted against total biomass and stem volume, which indicated even spread above and below the zero line, with no systematic trend. This suggested that the use of the reciprocal of the first unweighted volume estimation as a weighting factor in this study appeared to be appropriate for reducing heteroscedasticity.

Table 4. Mean value of bias and standard error of estimates in different diameter classes for the models. Model 2 predicts total biomass and Model 3 predicts total stem volume. N = the number of sample trees in different diameter classes.

DBH cm	N	Model 2 Bias (kg) - SEE		N	Model 3 Bias(dm3) - SEE	
<5	1	-0.59	0	8	0.36	0.98
5-10	5	-0.54	2.18	42	0.22	1.79
10-15	13	0.76	8.00	51	-0.4	3.96
15-20	13	-1.93	13.26	51	0.67	14.03
20-25	16	0.54	24.78	35	-2.79	15.90
>25	9	-0.07	26.80	17	6.73	26.82

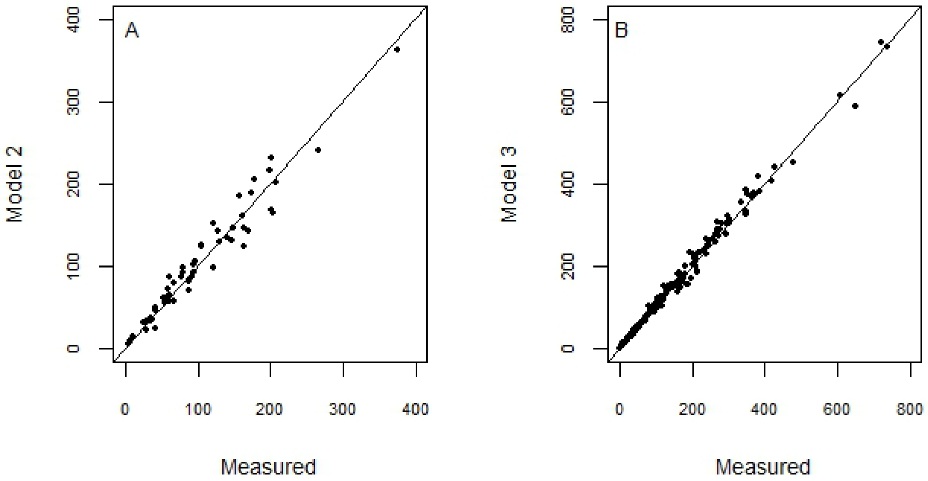

Figure 2. The 1:1 line for measured and predicted values of total aboveground biomass (kg) for Sitka- and white spruce (A) and total stem volume (dm^3) for Sitka spruce in Iceland (B).

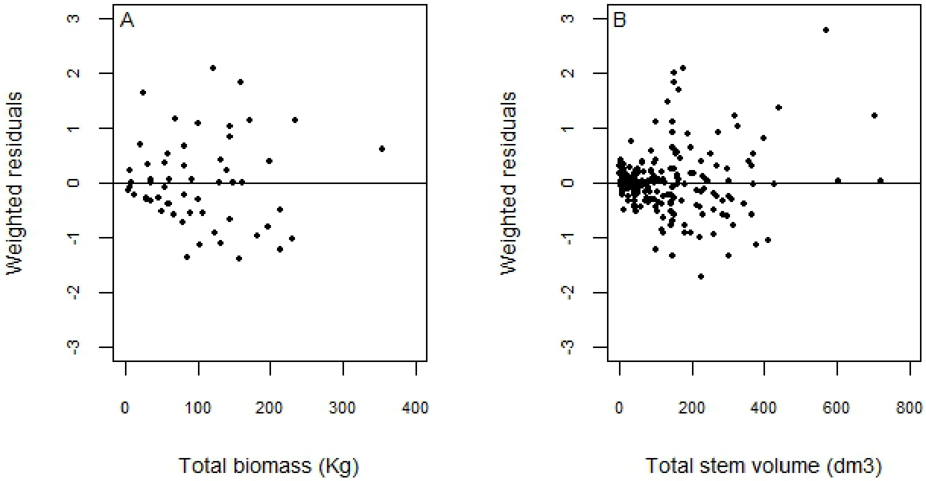

Figure 3. Residual plots for biomass model 2 (A) and stem volume model 3 (B).

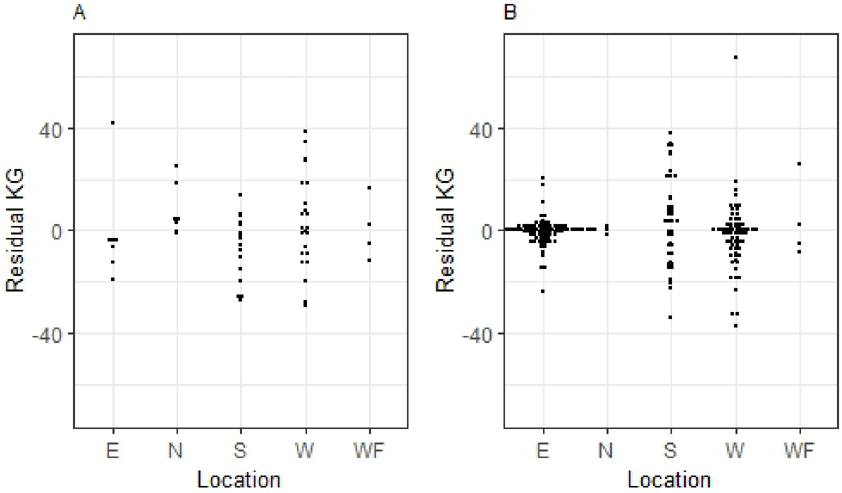

Figure 4. Residual plot of Sitka- and white spruce total biomass plotted by location (A) and Sitka spruce stem volume plotted by location (B). E is East Iceland, N is North Iceland, S is South Iceland, W is West Iceland and WF is the West Fjords.

As can be seen in Figure 4 A and B, very few sample trees represent the West Fjords (WF), and North Iceland (N). For North Iceland, an overestimation of total biomass seems to be the case. For South (S) and East Iceland (E), there seems to be a slight underestimation in the prediction (Figure 4 A). Residuals of biomass estimates from East Iceland had an outlier, but the rest of the residuals were closely grouped together, a bit under 0 (Figure 4 A). The normality test of residuals suggested that the residuals were normally distributed (data not shown). For West Iceland and the West Fjords, the residuals were well spread around 0 and the model seemed to give a good prediction. The volume prediction was rather good, and the residuals were well spread around 0. West Iceland had an outlier, and the variance was higher there and in the South Iceland compared to other locations (Figure 4 B).

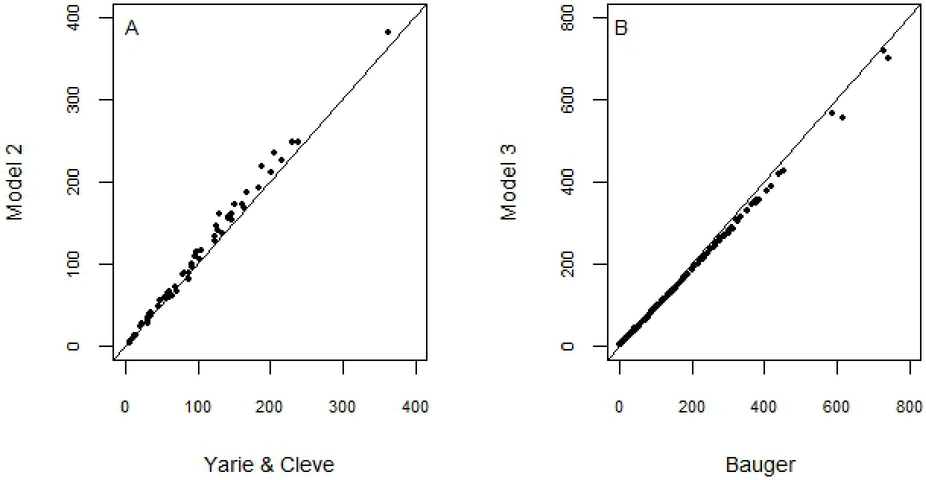

Figure 5. A graphical comparison between earlier published models for: A) above ground biomass (kg) of white spruce forests from interior Alaska (Yarie & Cleve 1983) and our biomass model 2; and B) stem volume (dm^3) model of Sitka spruce plantations on the west coast of Norway (Bauger 1995) and our volume model 3.

For the aboveground biomass model, the results for white spruce by Yarie and Cleve (1983) were used for comparison in the evaluations. This was done because in this study Sitka spruce and white spruce were combined and treated as one species. The reference study for stem volume was by Bauger (1995), which was based on samples from Sitka spruce plantations on the west coast of Norway. The reference studies used the same independent variables as the models evaluated in this study. Both reference studies showed some important differences from models in this study in predicting the total aboveground biomass and total stem volume

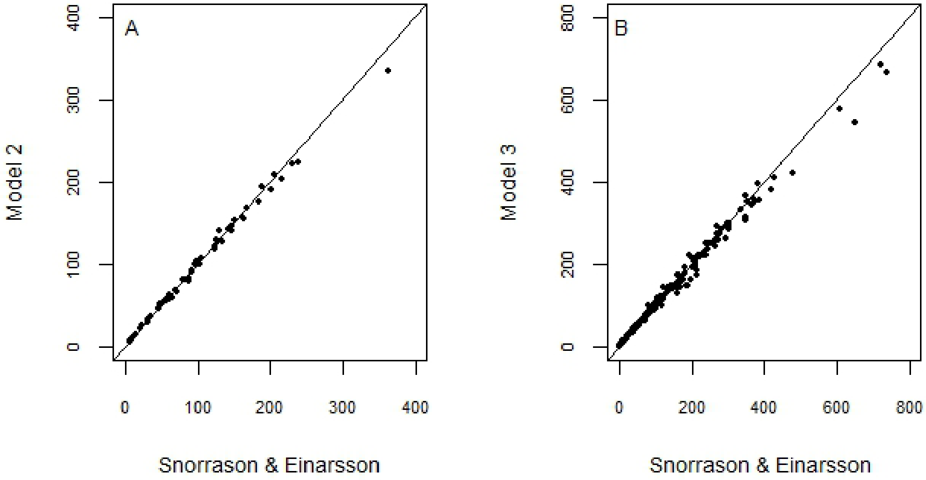

Figure 6. The 1:1 line of predicted values with the new models a) total biomass (kg) of Sitka- and white spruce and b) stem volume (dm^3) of Sitka spruce, compared to the estimated values obtained by using the models developed by Snorrason and Einarsson (2006).

of the reference model. The reference studies slightly overestimated the total aboveground biomass and underestimated the stem volume, especially for larger trees (Figure 5, A and B).

As can be seen in Figure 6 (A and B), the models developed by Snorrason and Einarsson (2006) clearly underestimate the total biomass and total stem volume compared to the present models, when they are used outside their data range.

DISCUSSION

In this study we present new aboveground biomass models for combined data from Sitka spruce and white spruce in Iceland and stem volume models for Sitka spruce. The models predict the total aboveground biomass and stem volume above the stump. The reliability of estimates of aboveground biomass and total stem volume depends on the range and extent of the sample data and how well the models fit this sample data (Akindele & LeMay 2006). The data in this study were obtained from regions in Iceland where the main forestry activity has taken place during the last 60 years and where the oldest and largest trees are located (Figure 1). The data represented various types of climates and soil and stand productivity conditions in Iceland. In some parts of the country, such as in the WF and N regions, sparse data were available for developing the new models. In these areas more uncertainty is involved in predicting total biomass and total stem volume. The data used for developing the volume model were from five different research projects, and part of the data was from a provenance trial. Only two provenances from the trial were used in the study, and only one of them was in general use in Iceland. Regarding the provenance effect on tree taper, a study conducted on European larch trees in Poland found no distinct variation in stem form among tested larch populations, and differences between compared provenances in respect to stem taper and form were the results of differences in tree height and diameter (Socha & Kulej 2007). The new models for spruce presented in this paper use the same independent variables and to some extent the same data as the older models for the two species in Iceland (Snorrason & Einarsson 2006), but they use a wider approach and have a different form than the older ones.

The models presented here all provide a logical relationship of DBH and H with stem volume and aboveground biomass. It is well known that including H may not always lead to substantial improvement in the goodness of fit for biomass or volume models (Ter-Mikaelian & Korzukhin 1997). This is more often the case where the sample is from a restricted local population and the ratio between the height and diameter of the trees has little variation. The aboveground biomass and stem volume models presented here were developed using data from a large geographical range. Using H as a second variable always improves both R^2 and SEE for these models during the development process (data not shown).

The relationship is also dependent on the stand density because density will affect the variation of crown structure and can significantly change the growing space and resource acquisition of trees (Qichang et al. 2022). If the forest practice is changed, the models may need to be updated, perhaps with stand density as an independent variable in the models. That could be the case, because from 1990 to 2020 the recommended planting density in Iceland has decreased from 4000 down to 2500 trees per hectare (Skógræktin 2020).

The foreign reference studies overestimated the total aboveground biomass and underestimated the stem volume, especially for larger trees (Figure 5, A and B). The difference was small but clearly shows the necessity to develop specific biomass and volume equations for Icelandic conditions. When the geographical range of the sample data is large, the divergent growth conditions may be reflected in more variation in the height to diameter ratio (Marklund 1987, Wirth et al. 2004).

It was also shown in Figure 6 that the existing Icelandic models of Snorrason and Einarsson (2006) underestimate the total biomass and total stem volume when they are used outside their data range. This justifies the work presented here and clearly shows the necessity to both develop specific volume and biomass models for Icelandic conditions and to update the country-specific models regularly as the trees and forest stands get older and taller.

General national models for prediction of forest biomass over a wide range of forest types can lead to large errors in the prediction of forest biomass of a specific site (Schroeder et al. 1997, Brown 2002). This may be due, in part, to different management (degree of self-thinning, crown characteristics) or climatic conditions (Black et al. 2004). To evaluate the model prediction, Iceland was divided into 5 regions (South, West, West Fjords, North and East), and the performance of the models in different regions were analysed and compared. This had not been done previously in Iceland. There were some signs of overestimation in the total biomass prediction in the North region and a sign of underestimation in the East and South (Figure 4 A). A slight underestimation was also noticed in volume prediction for the total stem volume in West Iceland, but in general the volume model seemed to predict stem volume fairly well in all locations (Figure 4 B).

For future work, more sample trees from North Iceland and the West Fjords are clearly needed, as well as in other areas, for developing updated models when forests get older and trees larger.

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