Single-tree biomass and stem volume functions for eleven tree species used in Icelandic forestry

ARNÓR SNORRASON

AND

STEFÁN FREYR EINARSSON

Icelandic Forest Research, Mógilsá, IS-116 Reykjavik, Iceland
E-mail: arnor@skogur.is
E-mail: stefan@alta.is

ABSTRACT

In this study we made destructive measurements on sample trees of eleven tree species from plantations spread around the main island of Iceland. These species are downy birch (*Betula pubescens*), rowan (*Sorbus aucuparia*), feltleaf willow (*Salix alaxensis*), dark-leafed willow (*Salix myrsinifolia*), black cottonwood (*Populus trichocarpa*), Sitka spruce (*Picea sitchensis*), Engelmann spruce (*Picea engelmannii*), white spruce (*Picea glauca*), Norway spruce (*Picea abies*), lodgepole pine (*Pinus contorta*), and Siberian larch (*Larix sibirica*). The aim was to develop single-tree functions for stem volume and above-ground biomass compartments for each species or for groups of related species, with stem diameter and height as the independent variables. In this article the results of these analyses are shown and comparisons are made with other functions created elsewhere for the same species and variables. The results provide useful functions for stem volume, stem biomass and total above-ground biomass for most species. Functions for live and dead branches, foliage and crown were mostly of a lower quality and disqualified as allometric estimators. Comparisons with other functions revealed a good fit for some species, but also highlighted the necessity for creating and applying specific functions for Iceland.

Key words: black cottonwood, biomass functions, Engelmann spruce, downy birch, feltleaf willow, lodgepole pine, rowan, Siberian larch, Sitka spruce, volume functions, white spruce

YFIRLIT

Lífmassa- og bolrúmmálsföll fyrir ellefu trjátegundir í skógrækt á Íslandi

Í rannsókninni sem hér er kynnt var úrtak trjáa af ellefu trjátegundum sem dreift var um allt land, fellt og mælt haustin 2001 og 2002. Trjátegundirnar ellefu eru: ilmbjörk, ilmreynir, alaskavíðir, viðja, alaskaösp, sitkagreni, blágreni, hvítgreni, rauðgreni, stafafura og síberíulerki. Markmið mælinganna var að gera föll þar sem hægt er, með mælingum á þvermáli og hæð, að áætla bolrúmmál og lífmassa trjánna ofanjarðar. Þannig föll voru gerð fyrir hverja tegund eða sameiginlega fyrir skyldar tegundir eftir því sem hentaði hverju sinni. Í greininni eru niðurstöður á greiningu fallanna kynntar og þau borin saman við sambærileg föll sem gerð eru fyrir önnur úrtaksþýði sömu tegunda eða tegundahópa. Megin niðurstaðan er að þessi rannsókn hefur fætt af sér nothæf föll fyrir bolrúmmál, lífmassa bols og heildarlífmassa ofanjarðar fyrir allar trjátegundirnar. Aftur á móti reyndust föll fyrir krónu, lifandi greinar, dauðar greinar, nálar og barr síðri og ekki nothæf sem spámetill fyrir fyrrnefndar breytur.

INTRODUCTION

Functions for estimating volume and mass of trees from basic growth measurements are fundamental when it comes to assessment of resources of wood, biomass and carbon in forests and woodlands. Methods to estimate the size of the stem of each tree in volume units have a long history (Husch et al. 1972), but mass estimates are a younger but growing sector in forest mensuration science (Pardé 1980). Measurements of volume and mass are laborious and costly, comprising felling and complicated measurements of the trees. Methods to estimate these dimensions have consequently been developed, using indirect measurements with the help of functions that describe mathematically the relationship between the volumes or the mass and other more easily measured variables. The most commonly used of these variables are the diameter of the stem and the height of the tree (Näslund 1947, Vestjordet 1967). These functions are now often determined with the help of linear regression or multiple regression if there is more than one measured variable (Crow 1988, Parresol 1999). Many papers give examples of such functions, both for the volume and the various mass components of single trees (Johnstone 1970, Eriksson 1973, Czapowskyj et al. 1985, Marklund 1987, Wirth et al. 2004) and some overview articles address these questions from different angles (Stanek & State 1978, Gholz et al. 1979, Ter-Mikaelian & Korzukhin 1997). Although these functions have much in common, their geographical validity varies; some of them are based on a sample taken from only one stand, whereas others were built on countrywide samples.

The goal of the present work was to develop single-tree functions for stem volume and the total and partial above-ground biomass for some tree species that are among the most commonly used in Icelandic forestry. These species are:

1. Downy birch, *Betula pubescens* Ehrh.
2. Rowan or mountain ash, *Sorbus aucuparia* L.
3. Feltleaf willow, *Salix alaxensis* Cov.
4. Dark-leafed willow, *Salix myrsinifolia* Salisb.
5. Black cottonwood, *Populus trichocarpa* Torr. & Gray
6. Sitka spruce, *Picea sitchensis* (Bong.) Carr.
7. Engelmann spruce, *Picea engelmannii* Parry
8. White spruce, *Picea glauca* (Moench) Voss
9. Norway spruce, *Picea abies* (L.) Karst.
10. Lodgepole pine, *Pinus contorta* Dougl.
11. Siberian larch, *Larix sibirica* Ledeb.

The resulting functions for the above-mentioned species should be valid for populations of these species in plantations in Iceland.

Furthermore, comparisons were made to other functions created elsewhere for the same dependent and independent variables, primarily from Scandinavian countries or areas where the introduced tree-species originated.

Such functions would greatly improve estimates of stem volume, biomass and carbon stocks on an area basis when used with data from woodland and forest inventories from Iceland and will furthermore improve the reporting of carbon stock and carbon stock changes in woodlands and forests in Iceland according to the *Good Practice Guidance for Land Use, Land-Use Change and Forestry* (IPCC 2003). In this way this work contributes to the fulfilment of the obligations of the Kyoto protocol (United Nations 1997), which was the main motivation for official funding of the research.

MATERIALS AND METHODS

Choice of sites and trees

The population used for sample tree harvesting consisted of measurement plots from an earlier research project dealing with the growth potential of the same eleven tree species in Iceland. The total number of plots in that project was 1,940, and the plots were spread as evenly as possible around the whole country for each species. The first criterion applied when choosing sample trees was that the plots had to be in a closed forest or, for the two willow species, in unpruned shelterbelts. Only 531 of the plots fulfilled this first criterion. All trees on the selected plots were put in a population pool for the sampling of harvest trees. The number of possible harvest trees was 13,189. The goal was to harvest and measure as many as 500 trees. For the most important species in Icelandic forestry, which are feltleaf willow, black cottonwood, downy birch, Siberian larch, Sitka spruce and lodgepole pine, the goal was to sample up to 60 trees for each species. For the five remaining species the target was 28 trees per species.

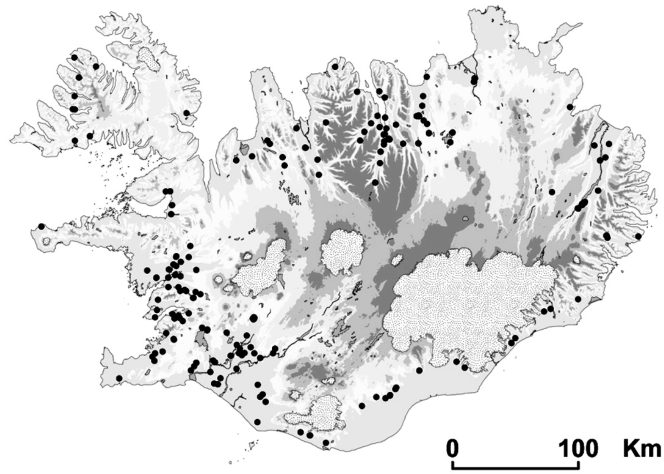

Figure 1. Location of plots where trees were harvested and measured.

To get an even distribution of dimensions, the trees for each species were classified in equally sized basal area classes. In each class, a similar number of trees was randomly chosen for harvesting. The same number of trees was chosen in each basal area class to serve as spare trees if the chosen trees could not be harvested for some reason or did not qualify after examination in the field. In this process the total number of trees was decreased, in particular due to a shortage of trees in the highest basal area classes. Extraordinary trees or solitary trees (e.g., that were severely damaged, or located in a border zone) were omitted.

The total number of trees harvested and measured in the study was 271. To supplement the data set, an additional 36 trees measured in the same manner in another study (Snorrason et al. 2002) were included. These additional trees were tested beforehand to see if they, as a sample group from a restricted part of the population, were different from the measured trees in the main population. The geographical distribution of plots where trees were harvested and measured is shown in Figure 1.

Measurement of harvested trees

Field measurements were carried out in 2001 and 2002 during August and September, when the vegetation was at its peak, the time recommended for carrying out biomass studies (Grier et al. 1981). Diameter was measured at breast height, 1.3 m above ground level ($d_{1.3}$) for all species except feltleaf willow, dark-leafed willow, rowan and downy birch, where the diameter was measured at 0.5 m above ground level ($d_{0.5}$). This was done because these species tend to branch heavily before reaching breast height. Moreover they have little tendency to basal swelling. Total stem volume was found by sectioning (Philip 1994). The length of each section was 5% of height under breast height but 10% of height over breast height. The harvested trees were divided into dead and living branches and stems, and each compartment was weighed for total fresh mass. Sub-samples were immediately taken from each compartment and weighed for fresh mass and later dried at 80°C and weighed again for dry mass.

Data analysis

Six different biomass components and the stem volume were calculated from the data collected. Biomass was calculated for dead branches, live branches (without foliage), foliage, stem, crown and total above-ground biomass. Tree crown was defined as the sum of foliage, live and dead branches. The volume was the total volume of the main stem including bark, from the top to the stump (defined as 1% of tree height).

To describe the relationship between the dependent and independent variables, we applied multiple linear regression on data transformed to a natural logarithm, which is a common procedure when describing volume or biomass in functions with diameter and height as the independent variables (Parresol 1999). The general function used was:

$$\ln Y = \mathrm{a} + b \times \ln d + \mathrm{c} \times \ln h \qquad (1)$$

where:

Y = stem volume (in dm^3), stem biomass, crown biomass, biomass of living or dead branches or total biomass above-ground (in kg).

a, b and c = coefficients calculated by regression

d = diameter (cm) at 1.3 m height or at 0.5 m height from ground level

h = length (m) of main stem from stem base to top of tree.

Statistical analyses were carried out with the multiple linear regression module of the SPSS (SPSS-Inc. 1999) statistical program package and with the linear regression module of SigmaPlot software (SPSS-Inc. 2000).

Residuals were examined graphically, both for outliers and linear fitting. All outliers were inspected for data punch errors and extraordinary growth environment of source trees. Trees were only removed from the data set if they were truly growing under extreme conditions. Functions of related species and species with similar stem and crown form were compared and tested for the hypothesis that they estimated the same population regression model (Zar 1999). For those populations that could be combined, only the mutual functions are presented.

As quality indicators of the fitted functions we used the Durbin-Watson statistic of correlation between the residuals (Neter et al. 1985), the Kolmogorov-Smirnoff test of normal distribution of the residuals and the modified Levene test of homogenity as a test of constant variance (Zar 1999), together with the coefficient of variation (CV) as defined below.

The functions obtained were converted from logarithmic to real form. A general equation on a retransformed form is:

$$Y = e^{(a+\beta)} \times d^b \times h^c \qquad (2)$$

where:

Y = stem volume (in dm^3), stem biomass, crown biomass, biomass of living or dead branches or total biomass above ground (in kg)

a, b and c = coefficient calculated by regression

d = diameter (cm) at 1.3 m height or at 0.5 m height from ground level

h = length (m) of main stem from stump to top of tree

$\beta = S_e^2/2$, where Se is the standard error of the regression. β is a correction factor to correct for logarithmic bias, as described by Baskerville (1972).

In addition to the function we display the application range for each regression in terms of tree diameter and height. We also display the coefficient of variation (CV) as an indicator of variation around the predicted value. CV was calculated according to the equation given by Marklund (1987):

$$CV = 100\% \times \sqrt{e^{S^2} - 1} \qquad (3)$$

Finally we carried out a graphical comparison of values predicted with a number of functions presented in this paper with values predicted with other functions found in the literature for the same species.

RESULTS

In Table 1 we display the functions we consider useful allometric estimators for appropriate dependent variables. The criteria for selection were carried out in two steps. First we examined the quality indicators of the regression, namely the Durbin-Watson statistics of correlation between the residuals, a test of normal distribution of the residuals, and a test of constant variance. If more than two of these statistics did not meet the requirements of the

Table 1. Single tree volume and biomass functions developed in this study.

Species and range of independent variables	Dependent variable	Inde-pendent variables	Function	CV[1]	N[2]	R^{2}[3]
Norway spruce $D_{1,3}$: 2.7 - 27.9 cm H: 2.7 - 12.0 m	Volume	$D_{1,3}$, H	Volume = $0.1299d^{1.6834}\ h^{0.8598}$	10.50	16	0.994
	Stem biomass	$D_{1,3}$, H	$DW_{stem} = 0.0712d^{1.637}\ h^{0.7436}$	13.70	16	0.989
	Life branches biomass	$D_{1,3}$, H	$DW_{life} = 0.0653d^{2.9955}\ h^{-1.3501}$	33.22	16	0.944
	Total biomass	$D_{1,3}$, *H**	$DW_{total} = 0.2465d^{2.12}\ h^{-0.167}$	17.20	16	0.981
	Crown biomass	$D_{1,3}$, H	$DW_{crown} = 0.2425d^{2.7517}\ h^{-1.3456}$	24.86	16	0.959
Engelmann spruce $D_{1,3}$: 1.4 - 12.7 cm H: 1.7 - 12.7 m	Volume	$D_{1,3}$, H	Volume = $0.4693d^{1.311}\ h^{0.781}$	25.88	15	0.968
	Stem biomass	$D_{1,3}$, *H**	$DW_{stem} = 0.2288d^{1.239}\ h^{0.717}$	25.76	14	0.967
	Total biomass	$D_{1,3}$, *H**	$DW_{total} = 0.9211d^{1.438}\ h^{0.102}$	31.68	14	0.927
Sitka spruce & white spruce $D_{1,3}$: 4.9 - 28.6 cm H: 4.8 – 15.4 m	Volume	$D_{1,3}$, H	Volume = $0.0739d^{1.7508}\ h^{1.0228}$	8.91	56	0.993
	Stem biomass	$D_{1,3}$, H	$DW_{stem} = 0.0558d^{1.5953}\ h^{0.9336}$	13.27	56	0.981
	Total biomass	$D_{1,3}$, H	$DW_{total} = 0.1334d^{1.8716}\ h^{0.4386}$	17.96	56	0.965
	Crown biomass	$D_{1,3}$, *H**	$DW_{crown} = 0.087d^{2.287}\ h^{-0.2897}$	31.28	56	0.905
Lodgepole pine $D_{1,3}$: 4.2 - 26.3 cm H: 2.8 - 12.8 m	Volume	$D_{1,3}$, H	Volume = $0.1491d^{1.6466}\ h^{0.8325}$	12.97	48	0.983
	Stem biomass	$D_{1,3}$, H	$DW_{stem} = 0.0669d^{1.5958}\ h^{0.9096}$	12.99	48	0.983
	Total biomass	$D_{1,3}$, H	$DW_{total} = 0.1429d^{1.8887}\ h^{0.4332}$	19.75	48	0.960
Siberian larch $D_{1,3}$: 3.3 - 31.6 cm H: 3.0 - 20.0 m	Volume	$D_{1,3}$, H	Volume = $0.0983d^{1.551}\ h^{1.1483}$	10.90	44	0.995
	Stem biomass	$D_{1,3}$, H	$DW_{stem} = 0.0444d^{1.4793}\ h^{1.2397}$	13.51	44	0.992
	Total biomass	$D_{1,3}$, H	$DW_{total} = 0.1081d^{1.53}\ h^{0.9482}$	17.64	44	0.984
Downy birch & rowan $D_{0.5}$: 2.1 - 29.8 cm H: 2.1 - 11.6 m	Volume	$D_{0,5}$, H	Volume = $0.0452d^{1.8091}\ h^{1.0487}$	14.39	53	0.986
	Stem biomass	$D_{0,5}$, H	$DW_{stem} = 0.0295d^{1.9451}\ h^{0.7672}$	19.48	52	0.975
	Total biomass	$D_{0,5}$, *H**	$DW_{total} = 0.0634d^{2.1552}h^{0.2877}$	23.64	43	0.945
Feltleaf willow $D_{0.5}$: 3.1 - 18.6 cm H: 2.3 - 7.8 m	Volume	$D_{0,5}$, H	Volume = $0.0687d^{1.8074}\ h^{0.7659}$	14.90	30	0.982
Dark-leafed willow $D_{0.5}$: 2.4 - 23.9 cm H: 1.9 - 8.8 m	Volume	$D_{0,5}$, H	Volume = $0.1588d^{1.2174}\ h^{1.1248}$	28.76	15	0.949
Feltleaf willow & dark-leafed willow $D_{0.5}$: 2.4 - 23.9 cm H: 1.9 - 8.8 m	Stem biomass	$D_{0,5}$, H	$DW_{stem} = 0.0364d^{1.7906}\ h^{0.7034}$	22.19	45	0.956
	Total biomass	$D_{0,5}$, H	$DW_{total} = 0.0348d^{1.9123}\ h^{0.8904}$	33.39	46	0.936
Black cottonwood $D_{1,3}$: 4.6 - 34 cm H: 4.6 - 20.7 m	Volume	$D_{1,3}$, H	Volume = $0.0732d^{1.6933}\ h^{1.0562}$	10.79	25	0.989
	Stem biomass	$D_{1,3}$, H	$DW_{stem} = 0.0379d^{1.581}\ h^{1.0795}$	14.90	22	0.980
	Total biomass	$D_{1,3}$, H	$DW_{total} = 0.0717d^{1.8322}\ h^{0.6397}$	14.43	22	0.980
	Crown biomass	$D_{1.3}$, *H**	$DW_{crown} = 0.0586d^{2.8285}\ h^{-1.0282}$	34.97	22	0.884

* The independent variable height (H) did not significantly improve the goodness of fit of the equation ($F_{0.05}$) (Zar 1999).
(1 Coefficient of variation.
(2 Number of observations.
(3 Coefficient of determination

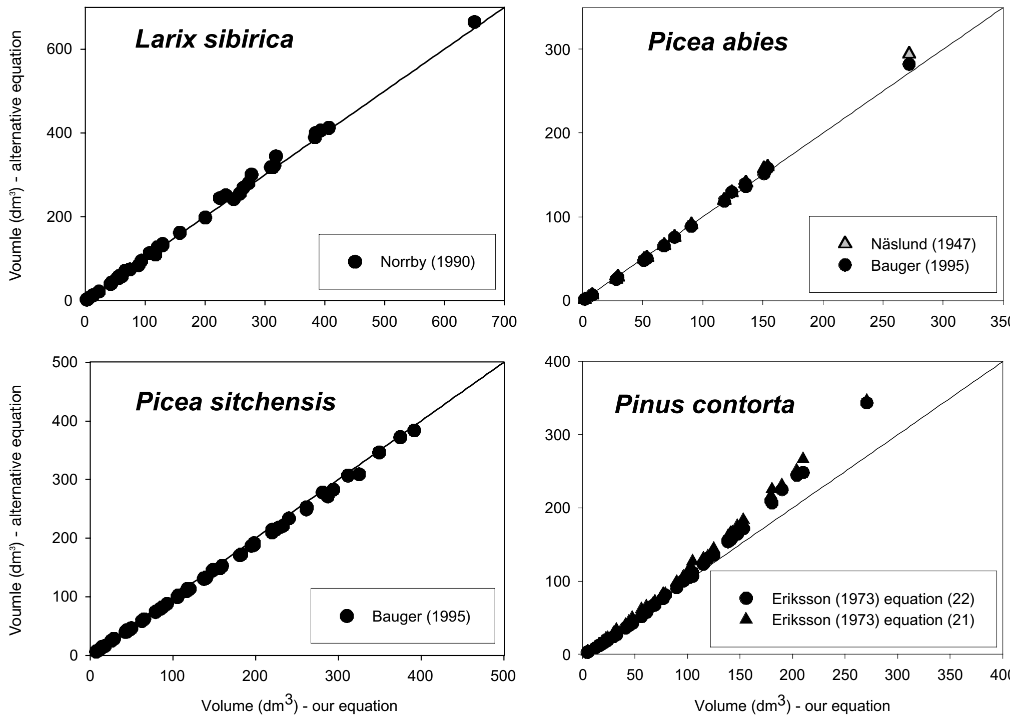

Figure 2. Stem volume functions from other publications compared to functions from the present study. The 1:1 line is also displayed in each case.

statistical methods of least squares, the respective regression was excluded. In the second step we looked at the coefficient of variation (CV) as an indicator of the preciseness of the regression estimating the dependent variable. We considered regressions with CV higher than 35% inapplicable as a practical tool to predict the dependent variable. This filtering left us with 29 functions out of 95 made initially.

Useful functions for stem volume, stem biomass and total biomass were available for all

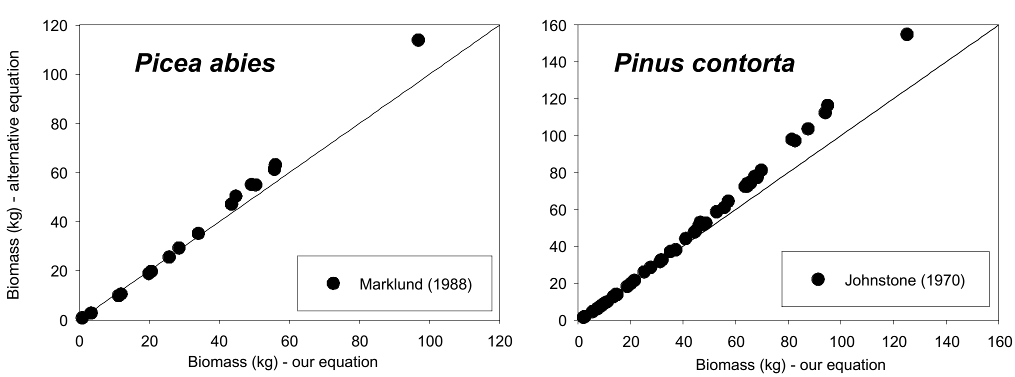

Figure 3. Stem biomass functions from other publications compared to functions from the present study. The 1:1 line is also displayed in each case.

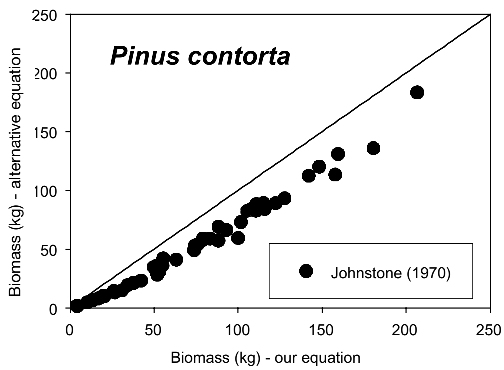

Figure 4. Total above-ground biomass function from Johnstone (1970) compared to function from the present study. The 1:1 line is also displayed.

species. Crown biomass functions were available for black cottonwood and for all the spruces except Engelmann spruce. A function for biomass of live branches is available for Norway spruce only. Functions for other variables were considered inapplicable. The quality of the functions did however differ to some extent. The most accurate and precise function for each species (or related species together) was the one for volume, with the coefficient of determination (R^2) > 0.98 and CV less than 15% for all species, except for Engelmann spruce which has a relatively high CV of almost 26%. Functions for stem biomass could also be regarded as good in most cases, with R^2 > 0.95 for all species, and a CV less than 15% for all species except Engelmann spruce, downy birch and rowan, and the willows, which had CVs in the range of 19 - 22 %. Even though having a high R^2 (> 0.927), the functions for total biomass do usually have a CV in the higher end of what was decided as an upper limit, or in the range of 17 - 33%. The total biomass function for black cottonwood does, however, have a rather low CV of ca. 14.4%. Functions for crown biomass have a CV higher than 30% except for Norway spruce where the CV is ca. 25%.

A number of comparisons were made between our functions and functions available from the literature for the same tree species and variables. These comparisons were, however, limited by the availability of comparable functions consisting of the same variables and therefore could not be carried out for all dependent variables or species. The results are presented in Figures 2-4.

DISCUSSION

A review of the variation around the regression lines (CV) for the species sampled in this study must take into consideration the country-wide distribution of sample trees and the relatively small sample size for each species. Compared to similar functions carried out on a country scale in Sweden for biomass compartments of Norway spruce, Scots pine (*Pinus silvestris*) and silver birch (*Betula verrucosa*) the variation was at a similar level although the numbers of sampling trees there were considerably higher than in the present study or 546, 488 and 240 trees respectively (Marklund 1988). There the CV for stem biomass was 17% for Norway spruce, 20% for Scots pine and 20% for white birch, compared to CVs ranging from 13% to 26% for the stem biomass functions presented in our study. Consequently, an increase in the number of sample trees from the level used in our research may not decrease the variation, or in other words improve the precision of the functions. However, to reduce the bias, the function should be revised and re-calibrated when enlarged materials from older plantations are available.

The accuracy or the fitness of our functions, interpreted as R^2, was however not as high as in the functions of Marklund (1988) where R^2 for stem biomass ranged from 0.990 to 0.994.

We always used both diameter and height as independent variables in the functions although it is well known that the height may not always lead to substantial improvement of the goodness of fit of single tree biomass equations (Ter-Mikaelian and Korzukhin 1997). The height is often aborted in the stepwise regression process. This is more often the case where the sample is from a restricted local population and the ratio between the height and the diameter of the tree has little variation. When the geographical range of the sample population is large, the more divergent growth conditions may be reflected in more variation in the height and diameter ratio. As shown in Table 1, height did significantly improve the goodness of fit of the majority of the regression models, or in 23 of 29 models. Other authors have also pointed out the necessity of using height, at least as a second independent variable, to lower the error of the model when making generic biomass functions (Marklund 1987, Wirth et al. 2004).

Graphical comparison with other functions with the same variables and same species gave divergent results. The volume functions shown in Figure 2 are very similar to our functions for Norway spruce, Sitka spruce and Siberian larch. The functions of Bauger (1995) for Norway spruce and Sitka spruce were based on samples from plantations on the west coast of Norway, but the Norway spruce function of Näslund (1947) was calculated from countrywide measurements in Sweden. The Siberian larch function is a local one for the larch plantations in the Hallormsstaður forest in eastern Iceland (Norrby 1990). The Eriksson (1973) volume functions for lodgepole pine were based on data from plantations in Sweden. These yielded higher values than our function, at least for larger trees (Figure 2). Similar differences were observed between our functions of stem biomass and the Marklund (1988) function of Norway spruce and the (Johnstone 1970) function of lodgepole pine from the Rocky Mountain region in Canada (Figure 3). On the other hand the function for total aboveground biomass in the same study yielded lower values than our function for lodgepole pine (Figure 4).

Although some of the published functions seem to yield results similar to ours, some of them obviously do not. Using them for an estimation of volume and biomass in Iceland would lead to biased results, a result that highlights the necessity of using specific functions for Icelandic conditions.

Further work with the present data set can be split into two categories: Firstly, the applicable functions have to be brought into common use as prediction tools. This is done by calculating an unbiased estimate, with statistical prediction intervals, as an uncertainty indicator for each real combination of diameter and height. Secondly, other variables should be tested to get a better regression fit for the compartments where the use of only diameter and height did not leave us with an acceptable equation. These could be crown width, crown height and diameter rank in the measurement plot as an indicator of social status of the tree in the forest.

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