Single tree biomass and volume functions for young Siberian larch trees (*Larix sibirica*) in eastern Iceland

BRYNHILDUR BJARNADOTTIR[1,2]
ANNA CECILIA INGHAMMAR [3]
MONA-MARIA BRINKER [4]
AND
BJARNI D. SIGURDSSON [3]

[1]Icelandic Forest Research, Mógilsá, 116 Reykjavík, Iceland

[2]Department of Physical Geography and Ecosystem Analysis, Lund University, Sweden
E-mail: brynhildur@skogur.is

[3]Agricultural University of Iceland, Hvanneyri, 311 Borgarnes, Iceland
E-mail: nem.annaci@lnhi.is
E-mail: bjarni@lbhi.is

[4]University of Applied Sciences, Eberswalde, Germany.
E-mail: mobrinker@web.de

ABSTRACT
In this study single tree biomass and volume functions for young larch plantation (*Larix sibirica*) in eastern Iceland are presented. In 2004 thirty trees were randomly chosen from a 12 year old plantation in eastern Iceland, harvested and weighed for dry mass. Biomass was calculated for branch wood, needles, stem, coarse roots excluding and including root stock, and total above-ground biomass. Volume was calculated for the main stem above ground and over bark. The results provide functions to estimate volume and various biomass components, using the independent variables diameter at 0.5 m height and tree height. The quality of the functions did, however, differ to some extent. Comparison of our functions with former published functions on Siberian larch in Iceland indicates that special biomass functions, as presented in this study, are needed to obtain unbiased estimates for small trees. Former functions typically underestimated the biomass of small trees.

Keywords: biomass functions, root biomass, stem volume, allometry, needle biomass

YFIRLIT
*Lífmassa- og rúmálsföll fyrir ung lerkitré (*Larix sibirica*) á Íslandi*
Í þessari rannsókn, sem er liður í að rannsaka til hlítar kolefnisbúskap ungrar lerkigróðursetningar, voru útbúin lífmassa- og rúmmálsföll fyrir ung lerkitré. Sumarið 2004 voru 30 tré felld og mæld í landi Vallaness á Fljótsdalshéraði. Út frá mælingum á þvermáli og hæð voru útbúin föll til að áætla lífmassa bols, greina, nála, og róta. Einnig voru útbúin föll sem áætla heildarlífmassa ofanjarðar og bolrúmmál. Niðurstöðurnar sýna mikilvægi þess að útbúa sérstök lífmassaföll fyrir ung tré í stað þess að nota föll sem gerð hafa verið fyrir eldri og stærri tré. Rannsóknin sýndi að áður birt lífmassaföll, útbúin fyrir eldri og stærri tré, höfðu tilhneigingu til að vanmeta lífmassa ungra trjáa.

INTRODUCTION

In order to estimate volume, biomass and carbon stock in forests, adequate and reliable allometric functions are needed. Allometric functions describe mathematically the relationship between the volume or the mass of the tree and other more easily measured variables, such as diameter at breast height (DBH) and/or the height (H) of the tree. The functions are usually determined with linear regressions on a log:log scale or a multiple regression if there is more than one measured variable (Pardé 1980). This approach has been widely used to estimate biomass and productivity in a variety of forest types (Pardé 1980, West 2004). The first allometric biomass functions appeared in the 1960s (Baskerville 1965), but since then a number of papers have been published on such functions (e.g. Marklund 1987, Johansson 1999, Wirth et al. 2004). Despite the fact that different allometric biomass and volume functions have much in common, they do not account for differences in shape and form caused by different tree species, age, site or management (Grier et al. 1981). Also, their geographical validity varies, with some functions based on a countrywide sample while others are based on a sample from only one stand. Therefore new biomass functions often need to be developed when tree species are introduced to new locations, such as is the case in Iceland (Snorrason & Einarsson 2006).

Up to now, almost all biomass functions have been calculated based on tall and mature trees, typically with at least 5 cm diameter at breast height (West 2004). Only a few allometric functions for young trees are available, and to our knowledge none for *Larix* sp. In Iceland, estimation of biomass for plantations established after 1989 now needs to be done. These plantations are referred to as “Kyoto forests” and their carbon accumulation is to be reported to the United Nations Framework Convention on Climate Change on an annual basis (Sigurdsson et al. 2007).

Siberian larch (*Larix sibirica* Ledeb.) is one of the most economically and ecologically important tree species of the Boreal zone. The area covered by Siberian larch amounts to nearly 14% of the total area of Russian forests (Schütt et al. 1994). The use of Siberian larch in forestry in the Nordic countries has been limited (Lyck & Bergstedt 2004). On the other hand, Siberian larch was the most planted tree species in Iceland during 1945-2000 (Pétursson 1999). It should be noted that there is some debate about the taxonomy within the *Larix* genera (Abaimov et al. 1998). Some authors differentiate between *Larix sukaczewii* Dyl. and *Larix sibirica* Ledeb.; the former originating west of the Ural Mountains and the rivers Ob and Irtysh, while the latter grows eastwards from that area (Simak 1979, Putenikhin & Martinsson 1995). Even if the material presented here originated from the western area, we prefer to use *L. sibirica* for both sub-species.

Because of forest policy and political changes, afforestation in Iceland increased very much in the late ‘80s and early ‘90s and today the present extent is ca. 2500 hectares per year (Pétursson 2002). During this time, Siberian larch has accounted for ca. 30% of the annual planting. The native mountain birch (*Betula pubescens* Ehrh.) and Sikta spruce (*Picea sitchensis* [Bong.] Carr.) are also used in similar proportions (Gunnarsson 2006). Siberian larch is therefore one of the key species in foresty in Iceland.

In 2006, Snorrason and Einarsson (2006) reported allometric functions for eleven tree species used in Icelandic forestry, including Siberian larch. For Siberian larch, volume, stem biomass and total biomass were estimated for trees with DBH ranging 3.3-31.6 cm. Sigurdardottir (2000) also reported allometric functions for different biomass components (roots included) of mature Siberian larch trees growing in East Iceland. The DBH of those trees ranged from 8.9 cm to 28.9 cm. Both these studies were made on older and larger trees, on average, than were used in the present analysis.

The present study is a part of a larger study on the carbon þuxes of a young Siberian larch plantation in eastern Iceland (Bjarnadottir et al.

2007). In order to estimate the carbon stock in the plantation, this particular study was initiated. The main goal was to create allometric single tree functions for biomass and stem volume for the young Siberian larch plantation. Functions were created for stem volume and a number of biomass components, including live branches, foliage, stem, roots excluding and including root stock, and total aboveground biomass. The outcome was then compared to other published functions already created for Siberian larch trees.

MATERIALS AND METHODS

Site description

The study took place on a 12 year old plantation in Vallanes, eastern Iceland (65°19'N, 14°56´W, elevation 60 m a.s.l.; Figure 1). The site was a grazed heathland pasture prior to afforestation in 1992, when it was protected from livestock grazing, ploughed and planted with Siberian larch of Pinega provenance, mixed with some lodgepole pine *(Pinus contorta* [Loudon] Douglas). The plantation covers approximately 60 ha and is typical of afforestation areas in eastern Iceland, containing not only homogeneous vegetation cover but also some patches of mire and inactive rock surfaces in between. The ground vegetation consists mainly of dwarf shrubs (*Betula nana* L. and *Vaccinium uliginosum* L.), grasses and bryophytes and the soil type is Brown Andosol, one of the most common soil types in Iceland (Arnalds 2004). In 2004, when the study took place, the average stand density at eight 100 m^2 circular plots randomly placed within the plantation was 3450 trees ha^{-1}, the average DBH was 1.4 cm, basal area at breast height was 0.73 m^2 ha^{-1} and the dominant height was 2.96 m. Further information on site conditions can be found in Bjarnadottir et al. (2007).

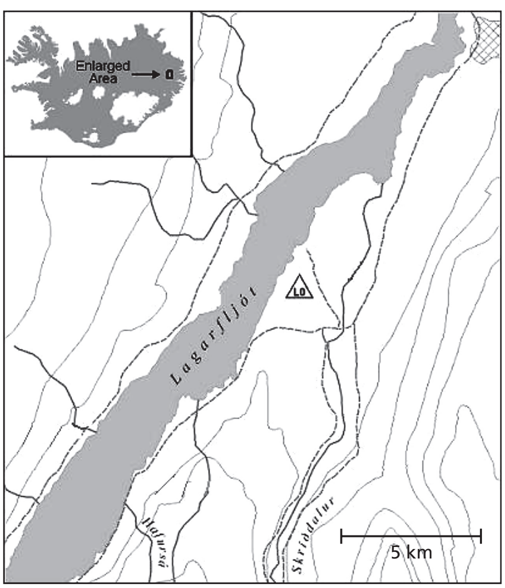

Figure 1. A map showing the study site in eastern Iceland. Triangle represents Vallanes (L0), where the study took place.

Measurement of harvested trees

Field measurements and harvesting of trees were carried out in August 2004, prior to needle fall. Thirty trees were randomly selected from the plantation and divided into six diameter classes. Diameter at 0.5 m height was used for classification, since some of the trees did not reach a height of 1.3 m. The diameter at 0.5 m height ranged from 1.2 to 9.0 cm. Prior to harvest, tree height and stem diameter were measured at 0.5 and 1.3 m above ground level. Trees were cut at ground level and no stump above ground was left on site. After felling, each tree was divided into three equally long sections. Each branch section, including the main stem, was put in paper bags. The samples were dried in an oven at 85 °C for 24 hours and then separated into needles and branch wood and then dried until they stopped loosing weight. All fully dried samples were weighed directly from the oven with 0.01 g accuracy.

In order to measure the stem volume, sectioning of the stem was used (Pardé 1980). From the middle of each stem section, a 3 cm thick stem disk was removed. The disk diameter was measured with bark. Later, the disks were also dried at 85 °C in an oven until they stopped losing weight so that their weight could be added to the total dry mass of each tree. Additionally nine trees were randomly chosen from the Vallanes plantation for harvesting of coarse roots in early October 2006. The trees were evenly distributed among the diameter classes and should therefore be representative of the area. The harvested trees were measured for height, diameter at breast height and diameter at 0.5 m height. The coarse roots were defined as the part of the main stem belowground (root stock) and roots with a diameter exceeding 2 mm (Vogt et al. 1996). All coarse roots and root stocks of the harvested trees were dug up, dried at 85 °C for 3 days, or until they stopped losing weight and then weighed for dry mass with 0.01 g accuracy.

Data analysis

Biomass was calculated for branch wood, needles, stem including bark, coarse roots including and excluding root stock, and total aboveground biomass. Volume was calculated for the main stem, over bark.

Three commonly used allometric models were tested:

$$Y = a \times D^b \quad (1)$$

$$Y = a \times D^b \times (D^2)^c \quad (2)$$

$$Y = a \times D^b \times H^c \quad (3)$$

where Y was the measured volume (dm^3) or biomass (g dry mass) of various components, *D* was the diameter at 0.5 m in cm, *H* was the height in m, and *a, b* and *c* were allometric coefÞcients calculated by regression. All the equations included the independent variable D_{50} (diameter over bark, at 50 cm height) and in Equation 3, the independent variable height was also included.

In order to describe the relationship between the dependent and independent variables, all variables were transformed to a natural logarithm (ln). This is a common procedure when describing volume or biomass in equations with diameter and/or height as the independent variables (Pardé 1980, West 2004). Statistical analysis was carried out with the multiple linear regression module of SigmaPlot software (SPSS-Inc 2000). Iteration was set to 10,000, tolerance to 0.000001 and step size to 1. After the calculations, the functions were converted from logarithmic to linear form, which can lead to an underestimate in the dependent variable. To compensate for this bias a correction factor described by Baskerville (1972) was used:

$$\beta = S_e^{\,2} / 2 \quad (4)$$

where S_e is the standard error of the regression and β is the correction factor to correct for logarithmic bias. CoefÞcient of variation (CV) was calculated according to Marklund (1987):

$$CV = 100\% * \sqrt{e^{S^2} - 1} \quad (5)$$

Criteria for selecting the better allometric functions with only one independent variable ($D_{0.5}$) were based on the higher coefÞcient of determination (r^2) and the lower CV.

RESULTS

In Table 1 functions for volume and various biomass components for young Siberian larch trees in Vallanes are displayed. Presented are the "best" allometric functions where only the independent variable $D_{0.5}$ was used and functions using both $D_{0.5}$ and H as independent variables. In most cases, the independent variable H did not signiÞcantly improve the aboveground functions. However, the belowground biomass showed a stronger relationship when using both $D_{0.5}$ and H as independent variables (Table 1). The quality of the functions, however, did differ to some extent. The most accurate and precise functions were the ones for total aboveground living biomass (r^2 = 0.991 and CV = 13.2%) and volume (r^2 = 0.991 and CV = 14%), using only $D_{0.5}$ as an independent variable (Table 1). Functions for stem, branch and needle biomass were of slightly lower quality, but still fairly accurate ($r^2 > 0.95$ and CV < 25%). The functions for roots excluding and including root stock, as mentioned above, showed the best correlation using both $D_{0.5}$ and H as independent variables ($r^2 > 0.95$ and CV < 23%).

Comparison was made between our "best"

functions for young larch trees and the functions already published by Snorrason and Einarsson (2006) and Sigurdardottir (2000) (Figures 2, 3 and 4). Total aboveground biomass was estimated by the different functions and linear regressions were carried out between the results. The regression slope for our "best" function and the one of Sigurdardottir (2000) yielded a low intercept (-1840) and steep slope (1.31; Figure 2). This indicated that it both underestimated the total biomass by almost 2 kg DM for the smallest trees compared to our function, but then overestimated it by almost as much for the tallest trees in this study. The regression line between our "best" function and Snorrason and Einarsson (2006) function had less negative intercept (1032) and a slope close to unity (0.96), which indicated that it predicted similar size-related change in total aboveground biomass as our function, but underestimated the total biomass of young trees by about 1 kg, irrespective of tree size (Figure 2).

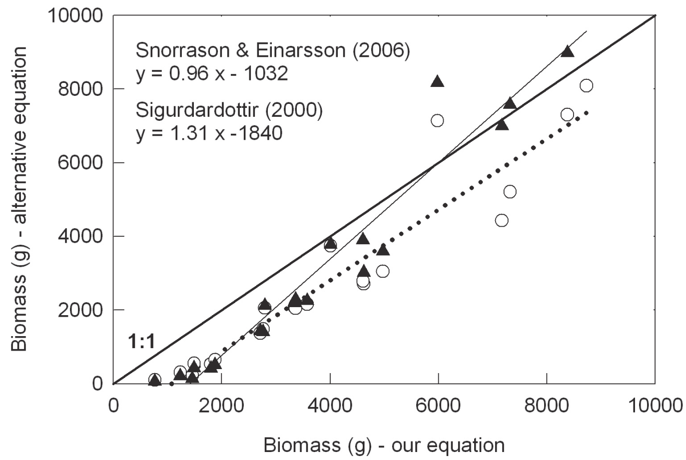

Figure 2. Comparison of allometric functions to estimate total aboveground biomass (g). Our "best" function is represented with 1:1 line. Circles represent the function from Snorrason and Einarsson (2006), Y = 0.1081 * $D^{1.53}$ * $H^{0.9482}$ and triangles the function from Sigurdardottir (2000), Y = -0.997 * $D^{2.3118}$. Fine and dotted lines indicate linear regressions.

The difference between our "best" stem biomass function and such functions made by Sigurdardottir (2000) and Snorrason and Einarsson (2006) showed a similar pattern (Figure 3). Again, the function developed by Sigurdardottir (2000) underestimated the stem biomass for the smallest trees and greatly overestimated the stem biomass for the taller trees. The function made by Snorrason and Einarsson (2006) slightly underestimated the stem biomass for the smallest trees but came close to our values for the taller trees (Figure 3).

Sigurdardottir (2000) did not develop a stem volume function and therefore we only compared our "best" function to Snorrason and Einarsson (2006) in Figure 4. The two functions were quite comparable, with an identical size-related difference in stem volume (slope of 1.01). The Snorrason and Einarsson (2006) function slightly underestimated the stem volume for our sample trees (intercept of -1.26 dm^3).

When functions for the biomass of coarse roots > 2 mm and root stock were compared to functions of total aboveground biomass the mean root to shoot ratio (R/S ratio) of 0.41 was found (Table 1). Of the aboveground biomass, stem mass ratio (SMR) was ca. 0.45 and branch mass ratio (BMR) ca. 0.35 for the young Siberian larch trees. The needle mass ratio (NMR) was the smallest and amounted to 0.12-0.17 of aboveground biomass.

DISCUSSION

The three allometric equations used in the present analysis have all been used in earlier studies. Equation (1) is the most commonly used allo-metric equation in the literature (Pardé 1980, West 2004). However, a number of other equations have been suggested by various authors (e.g., Baskerville 1965, Cannell 1982, Marklund 1987). In the present study we chose Equation (2) as an alternative to Equation

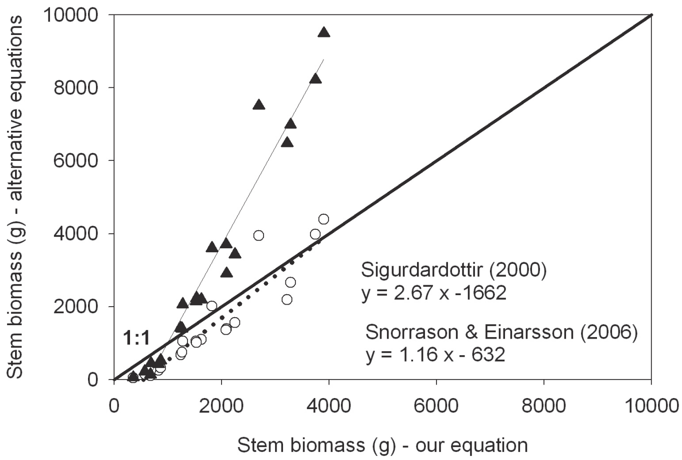

Figure 3. Comparison of allometric functions to estimate stem biomass (g). Our "best" function is represented with 1:1 line. Circles represent the function from Snorrason and Einarsson (2006), $Y = 0.0444 * D^{1.4793} * H^{1.2397}$ and triangles the function from Sigurdardottir (2000), $Y = -0.943 * D^{2.2024}$. Fine and dotted lines indicate linear regressions.

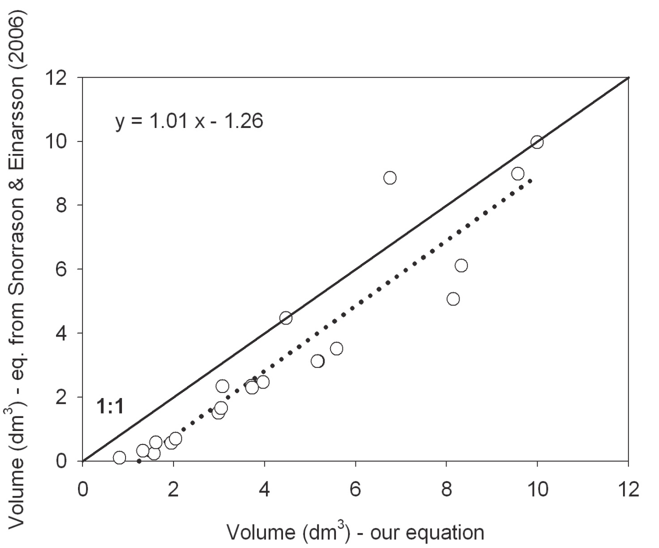

Figure 4. Comparison between Snorrason and Einarsson (2006) and our "best" function to estimate volume (dm^3). Our "best" function is represented with 1:1 line. Circles represent the function from Snorrason & Einarsson (2006), $Y = 0.0983 * D^{1.551} * H^{1.1483}$, where dotted line indicates linear regression.

to the equation used by Snorrason and Einarsson (2006) in making similar single tree functions for 11 tree species in Iceland.

To our knowledge, no published generic biomass functions exist for Siberian larch growing outside Iceland, at least in English literature. However, there are some studies that have reported biomass functions for other larch species. Rubatscher et al. (2006) reported biomass expansion functions for European larch (*Larix decidua* (L)) growing in Austria. Similarly, Zavitkovski and Strong (1984) and Zhou et al. (2002) reported biomass equations for the hybrid between Japanese and European larch (*L.× eurolepsis*) and Dahurian larch (*L. gmelini* Kuzneva), respectively. There are also some dominant height and yield tables for Siberian larch for northern Sweden (Martinsson 1995) and some allometric relationships to describe tree dimensions and stand volume for Siberian larch, tamarack (*L. laricina* Du Roy), European larch (*L. decidua* Mill.) and Japanese larch (*L. leptolepis* Gordon) (Gilmore 2001, Hakkila & Winter 1973). However, these can not be used for estimating the standing biomass of individual trees.

In Iceland, most emphasis has been placed on calculating dominant height and yield

(1). Johansson (1999) reported Equation (2) as a good equation for young Norway spruce trees (*Picea abies* (L.) Karst.) grown in Sweden. Equation (3) was chosen since it is identical

tables for Siberian larch (Norrby 1990, Karlsson 1990, Lindhagen 1990, Heiðarsson 1998, Pesonen 2006). As mentioned above, two papers have been published on biomass functions

Table 1. Volume and biomass functions for young Siberian larch trees in Iceland. Independent variable D is diameter at 0.5 m height in cm and H is tree height in m.

Dependent variables	Functions	Coefficient of determination, r^2	Coefficient of variation, %CV
Total biomass	$Y = 119.734 * D^{1.4251} * (D^2)^{0.2539}$	0.991	13.2
Stem biomass	$Y = 58.4554 * D^{1.3698} * (D^2)^{0.2616}$	0.990	13.5
Branch biomass	$Y = 31.5330*D^{2.1475}$	0.973	23.8
Needle biomass	$Y = 17.8470* D^{1.8092}$	0.956	26.0
Stem + branch biomass	$Y = 97.7451 * D^{1.4588} * (D^2)^{0.2551}$	0.990	21.4
Branch + needle biomass	$Y = 61.7708 * D^{1.4412} * (D^2)^{0.2462}$	0.981	25.5
Coarse roots + root stock	$Y = 31.7518 * D^{1.9433}$	0.952	13.9
Coarse roots	$Y = 22.5475 *D^{1.9374}$	0.934	19.4
Volume over bark	$Y = 0.1187 * D^{1.4130} * (D^2)^{0.2922}$	0.991	13.9
Total biomass*	$Y = 102.1374 * D^{1.8073} * H^{0.3191}$	0.987	15.9
Stem biomass*	$Y = 54.0065 * D^{1.5481} * H^{0.6363}$	0.988	15.1
Branch biomass*	$Y = 31.\ 9231* D^{2.1194} * H^{0.0401}$	0.972	24.3
Needle biomass*	$Y = 20.0248 * D^{1.5223} * H^{0.4095}$	0.957	26.1
Stem + branch biomass*	$Y = 83.4488 * D^{1.8387} * H^{0.3264}$	0.986	16.4
Branch + needle biomass*	$Y = 49.7391 * D^{1.9987} * H^{0.0854}$	0.977	21.5
Coarse roots + root stock	$Y = 19.8982 * D^{2.8750} * H^{-1.0856}$	0.967	19.2
Coarse roots	$Y = 12.4833 * D^{3.1116} * H^{-1.3681}$	0.957	22.0
Volume over bark*	$Y = 0.1022 * D^{1.7718} * H^{0.4829}$	0.986	16.8

* Height (H) did not significantly improve the goodness of fit of the function.

for Siberian larch (Sigurdardottir 2000, Snorrason & Einarsson 2006). Their main difference is that Sigurdardottir (2000) only used a few large sample trees from a restricted local population close to our study site, while Snorrason and Einarsson (2006) used a random sample from all over Iceland and measured more trees and included more size variations. Both studies were, however, based on a sample of older and taller trees than found in the present study and might therefore not apply to young trees. This was the case for Sigurdardottir (2000). When comparing our results to Snorrason and Einarsson (2006), however, a relatively good agreement was observed. There was a fixed underestimation in absolute biomass, but their model was a good predictor for size-related changes. This Þxed underestimation could be an effect of tree age (small size), but there are also some methodological differences between the studies that could explain it. Snorrason and Einarsson (2006) did not include the aboveground stump of the harvested trees in their analysis which clearly can lead to an underestimation of the aboveground biomass. Also, one must keep in mind the spatially limited sample population used in this study.

The functions of Snorrason and Einarsson (2006) have two independent variables, diameter and height. We therefore also chose to present our results with Equation (3) for better comparison with the existing functions. Height, however, did not signiÞcantly improve the allometric model for aboveground biomass in our study. This Þnding is in agreement with other studies, where the harvested trees came from a restricted local population or the ratio between the height and the diameter of the trees had little variation (Parresol 1999). Both circumstances apply to the present study. However, it has been pointed out that it is preferable to use height as a second independent variable to lower the estimation error of generic biomass functions (Marklund 1987, Wirth et al. 2004, Snorrason & Einarsson 2006).

The present study reports allometric functions for root biomass for young Siberian larch trees, yielding the average R/S ratio of 0.41 (root mass ratio, RMR, of 0.29). Only two other studies have been done on root biomass of Siberian larch in Iceland. Snorrason et al. (2002) excavated trees ranging between 3.5 and 8.4 m in height and found an average R/S ratio of 0.25 (RMR of 0.20). They deÞned coarse roots as roots with a diameter > 5 mm. Sigurdardottir (2000) also published R/S ratio for 50 year old Siberian larch trees, but since she deÞned coarse roots as roots with a diameter > 50 mm rather than the 2 mm used in the present study, any comparison was impossible. The difference in the reported R/S ratio between these two studies probably arises both from the lower diameter threshold in the present study and the age-difference of the sample trees. It is well known that young trees generally have relatively more biomass allocated to their root systems than older trees (Pardé 1980, Dickmann & Pregitzer 1992). Other references on R/S ratio or RMR of *Larix* sp. are scarce. Offenthaler and Hochbichler (2006) concluded that an R/S value of 0.22 was a reasonable approximation for mature European larch growing in subalpine areas in Austria, but the R/S ratio would increase to ca. 0.40-0.50 when the trees were growing close to their altitudinal limit. Our results are in the same range.

Very few studies have been done on root biomass in Iceland and we only know of one additional published study by Sigurdsson et al. (2001). They excavated 24 root systems of black cottonwood trees (*Populus tricocarpa* Torr. & Grey), ranging from 1.4 to 3.1 m in height. They used the 2 mm root diameter limit and found an average R/S ratio of 0.41 (RMR of 0.29). This is identical to the R/S ratio found in the present study for young Siberian larch. This may indicate that the age-related differences may be equally or possibly more important than species differences in R/S ratios.

In 2005, a new sample-based National Forest Inventory (NFI) was launched in Iceland (Sigurdsson et al. 2007). It is based on systematic sample plots, laid out in a 500 m vs. 1000 m sample grid in all mapped afforestation areas > 0.5 ha. These include mostly plantations, but in some cases the areas are seeded. A special emphasis by the Icelandic NFI is to estimate carbon stocks of so called ‘Kyoto-forests’, i.e. afforestation areas established after 1989. This is a relatively large area in Iceland, amounting to 74% of the 28,900 ha afforested by 2005 (Sigurdsson et al. 2007).

To date, mean annual C sequestration rates of 1.2 – 1.7 t C ha^{-1} yr^{-1} have been used to estimate C stock changes in all forest plantations in Iceland (Sigurdsson & Snorrason 2000, Snorrason et al. 2002). This estimate is valid for forest plantations up to 30-50 years of age, and has been applied for all tree species. It gives a conservative estimate of C sequestration, since average values for a number of 35-50 year old forest plantations have yielded as much as five times as high sequestration potentials (e.g. Sigurdsson et al. 2007, Snorrason et al. 2002, Sigurdardottir 2000). Such mean sequestration rates do not take into account the high variation in annual C sequestration depending on the age of plantations. Mean annual sequestration overestimates current annual sequestration rates in young plantations and underestimates the rate in middle-aged plantations. A better way to estimate C-sequestration in forest plantations is to measure the C-stocks in a forest inventory and apply either volume or biomass functions. If volume functions are used, information about wood density and biomass expansion factors needs to be added before the forest carbon stock can be derived (Einarsson et al. 2004). Therefore biomass functions are preferred for the Icelandic NFI, if available (Sigurdsson et al. 2007). After repeated measurements at two different times, the stock change method, as described in *Good Practice Guidance for Land Use, Land-Use Change and Forestry* (IPCC 2003), can be applied to estimate average C sequestration or C emission for a time period near to current time.

Former single tree volume and biomass functions are made for relatively old and large trees and rarely include trees younger than ca. 20-30 years of age with DBH of 3-5 cm. They should not be used outside the range of their development. If used, our results show that they underestimate smaller trees. The comparison of our functions to former published functions on Siberian larch in Iceland clearly shows the necessity for creating special biomass functions for young trees.

ACKNOWLEDGEMENTS

This work contributes to the ICEWOODS project funded by the Icelandic Research Council, to the SNS-CARBON project funded by the Nordic Forest Research Co-operation Committee and to the NECC project *(Nordic Centre for Studies of Ecosystem Carbon Exchange and its Interactions with the Climate System;* www.necc.nu), funded by the Nordic Council of Ministers and the joint Nordic Research Councils, NOS-N under the Climate Change Programme. The staff at Hallormsstaður field station deserve thanks for help in the field and Kjartan Kjartansson at Mógilsa for helping with drying and weighing samples.

REFERENCES

Abaimov AP, Lesinski JA, Martinsson O & Milyutin LI 1998. Variability and ecology of Siberian larch species. *Report from Dept. of Silviculture, No. 43,* Swedish University of Agricultural Sciences, Umeå, Sweden. 123 p.

Arnalds Ó 2004. Volcanic soils of Iceland. *Catena* 56, 3-20.

Baskerwille GL 1965. Estimation of dry weight of tree components and total standing crop in conifer stands. *Ecology* 46(6), 867-869.

Baskerwille GL 1972. Use of logarithmic regression in the estimation of plant biomass. *Canadian Journal of Forest Research* 2, 49-53.

Bjarnadottir B, Sigurdsson BD & Lindroth A 2007. Estimate of annual carbon balance of a young Siberian larch (*Larix sibirica*) plantation in Iceland. *Tellus* 59B, 891-899.

Cannell MGR 1982. *World forest biomass and primary production data.* Academic Press. 391 p.

Dickmann DI & Pregitzer KS 1992. The structure and dynamics of woody plant root systems. In: Mitchell CP (ed.) *Ecophysiology of short rotation forest crops.* Elsevier Applied Science, London, pp. 95-123.

Einarsson SF, Sigurdsson BD & Snorrason A 2004. Estimating aboveground biomass for Norway spruce (*Picea abies*) in Iceland. *Icelandic Agricultural Sciences* 17/18, 53-63.

Gilmore DW 2001. Equations to describe crown allometry of *Larix* require local validation. *Forest Ecology and Management* 148, 109-116.

Gunnarsson E 2006. Skógræktarárið 2005 (Annual planting in 2005). *Skógræktarritið 2006,* 94-102. (In Icelandic).

Grier CC, Vogt KA, Keyes MR & Edmonds RL 1981. Biomass distribution and above- and below-ground production in young and mature *Abies amabilis* zone ecosystems of the Washington Cascades. *Canadian Journal of Forest Reseach* 11, 155-167.

Hakkila P & Winter A 1973. On the properties of larch wood in Finland. *Communicationes Instituti Forestalis Penniae* 79(7). 90 p.

Heiðarsson L 1998. *Boniteringskurvor för Lärk* (Larix sukaczewii) *på Hallormsstaður, Island.* Naturbruksinstitutet Ekenäsenheten. Examensarbete i ämnet skogsmätning. 44 p. (In Swedish).

IPCC 2003. *Good Practice Guidance for Land Use, Land-Use Change and Forestry.* The Intergovernmental Panel on Climate Change (IPCC). J Penman, M Gytarsky, T Hiraishi, T Krug, D Kruger, R Pipatti, L Buendia, K Miwa, T Ngara, K Tanabe & F Wagner (eds). Institute for Global Environmental Strategies (IGES) 2108-11, Kamiyama-guchi Hayama, Kanagawa Japan, 240-0155. 570 p.

Johansson T 1999. Biomass production of Norway Spruce (*Picea abies* (L.) Karst.) growing on abandoned farmland. *Silva Fennica 33*(4), 261-280.

Karlsson L 1990. *Standortsfaktorer som indikatorer på boniteten för* Larix sukaczewii *och* Larix sibirica *på Island.* Examensarbete i ämnet skogsskötsel. Dept. of Silviculture, Swedish University of Agricultural Sciences, Umeå, Sweden. 21 p. (In Swedish).

Lindhagen A 1990. *Klimatets och årsmånens inverkan på tillväxten hos* Larix sukaczewii *och* L. sibirica *på Island.* Examensarbete i ämnet skogsskötsel. Dept. of Silviculture, Swedish University of Agricultural Sciences, Umeå, Sweden. 48 p. (In Swedish).

Lyck C & Bergsted A 2004. *Use and availability of Larch wood in Northern Europe – a literature review.* Report from the Royal Veterinary and Agricultural University, Unit of Forestry, Copenhagen, Denmark. 66 p.

Marklund LG 1987. *Biomass functions for Norway spruce* (Picea abies (L.) *Karst.) in Sweden,* Rep. No. 43. Department of Forest Survey, Swedish University of Agricultural Sciences, Umeå. 127 p.

Martinsson O 1995. Yield of *Larix suhaczewii* Dyl. in Northern Sweden. *Studia Forestalia Suecica* 196. 20 p.

Norrby M 1990. *Volym- och formtalsfunktioner för* Larix sukaczewii *och* Larix sibirica *på Island.* Examensarbete i ämnet skogsskötsel. Dept. of Silviculture, Swedish University of Agricultural Sciences, Umeå, Sweden. 41 p. (In Swedish).

Offenthaler I & Hochbichler E 2006. Estimation of root biomass of Austrian forest tree species. *Austian Journal of Forest Science* 123, 65-86.

Pardé J 1980. Forest biomass. *Forestry Abstracts* 41, 343-362.

Parresol BR 1999. Assessing Tree and Stand Biomass: A Review with Examples and Critical Comparisons. *Forest Science* 45 (4), 573-593.

Pesonen A 2006. *Modelling the Growth and Yield of Larch in Hallormsstaður, Iceland.* University of Joensuu, Faculty of Forestry. Master's thesis in Forest Planning and Economics. 91 p.

Pétursson JG 1999. Skógræktaröldin: Samanteknar tölur úr Ársriti Skógræktarfélags Íslands [The first 100 years of tree planting in Iceland]. *Skógræktarritið 1999,* 49-53. (In Icelandic).

Pétursson JG 2002. Skógræktarstarfið árið 2000. Tölulegar upplýsingar. [Tree planting in 2000. Statistics.] *Skógræktarritið* 2, 2002, 82-84. (In Icelandic).

Putenikhin VP & Martinsson O 1995. *Present distribution of* Larix sukaxzewii *Dyl. in Russia, Rep.* Report from Dept. of Silviculture, No. 38. Swedish University of Agricultural Sciences, Umeå, Sweden. 77 p.

Rubatscher D, Munk K, Stöhr D, Bahn M, Mader-Oberhammer M & Cernusca A 2006. Biomass expansion functions for *Larix decidua*: a contribution to the estimation of forest carbon stocks. *Austrian Journal of Forest Science* 123, 87-101.

Schütt P, Schuck HJ, Lang U & Roloff A 1994. *Enzyklopädie der Holzgewächse, Handbuch und Atlas der Dendrologie.* [Encyclopaedia of woody plants, compendium and atlas of geology], Ecomed, 1.edition, *Larix sibirica* III-1, 1-5. (In German).

Sigurdardottir R 2000. *Effects of different forest types on total ecosystem carbon sequestration in Hallormsstaður forest, eastern Iceland.* Ph.D. thesis. Yale University, 193 p.

Sigurdsson BD & Snorrason A 2000. Carbon sequestration by afforestation and revegetation as a means of limiting net-CO_2 emissions in Iceland. *Biotechnology, Agronomy, Society and Environment* 4, 303-307.

Sigurdsson BD, Thorgeirsson H & Linder S 2001. Growth and dry-matter partitioning of young *Populus trichocarpa* in response to CO_2 concentration and mineral nutrient availability. *Tree Physiology* 21, 941-950.

Sigurdsson BD, Snorrason A, Kjartansson B & Jonsson JA 2007. Total area of planted forests in Iceland and their carbon stocks and þuxes. In: Halldórsson G, Oddsdóttir ES & Eggertsson O (eds.) *Effects of afforestation on ecosystems, landscape and rural development.* pp. 211-217.

Simak M 1979. Larix sukaczewii: *naturlig utbredning, biologi, ekologi och fröanskaffningsproblem* [*Larix sukaczewii:* area of natural distribution, biology, ecology and seed problems], Report from Dept. of Silviculture, No. 1, Swedish University of Agricultural Sciences, Umeå, Sweden. 76 p. (In Swedish).

Snorrason A & Einarsson SF 2006. Single-tree biomass and stem volume functions for eleven tree species used in Icelandic forestry. *Icelandic Agricultural Sciences* 19, 15-24.

Snorrason A, Sigurdsson BD, Guðbergsson G, Svavarsdóttir K & Jónsson ÞH 2002. Carbon sequestration in forest plantations in Iceland. *Icelandic Agricultural Sciences* 15, 81-93.

SPSS-Inc 2000. *SPSS Base 10.0 Application Guide.* SPSS-Inc., Chicago, USA. 412 p.

Vogt KA, Vogt DJ. Palmiotto PA, Boon P, O´Hara J & Asbjornsen H 1996. Review of root dynamics in forest ecosystems grouped by climate, climatic forest type and species. *Plant and Soil.* 187,159-219.

West PW 2004. *Tree and Forest Measurement.* Springer-Verlag, Berlin. 167 p.

Wirth C, Schumacher J & Schulze E-D 2004. Generic biomass functions for Norway spruce in Central Europe - a meta-analysis approach toward prediction and uncertainty estimation. *Tree Physiology* 24, 121-139.

Zavitkovski J & Strong TF 1984. *Biomass production of 12-year-old intensively cultured* Larix eurolepsis. Research Note NC-321. U.S.D.A. Forest Service. 3 p.

Zhou G, Wang Y, Jiang Y & Yang Z 2002. Estimating biomass and net primary production from forest inventory data: a case study of China's *Larix* forests. *Forest Ecology and Management* 169, 149-157.

Manuscript received 7 July 2007
Accepted 27 September 2007