Biomass allometries and coarse root biomass distribution of mountain birch in southern Iceland

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ABSTRACT
Root systems are an important pool of biomass and carbon in forest ecosystems. However, most allometric studies on forest trees focus only on the aboveground components. When estimated, root biomass has most often been calculated by using a fixed conversion factor from aboveground biomass. In order to study the size-related development of the root system of native mountain birch (*Betula pubescens Ehrh. ssp. czerepanovii*), we collected the coarse root system of 25 different aged birch trees (stem diameter at 50 cm length between 0.2 and 14.1 cm) and characterized them by penetration depth (< 1 m) and root thickness. Based on this dataset, allometric functions for coarse roots (> 5 mm and > 2 mm), root stock, total belowground biomass and aboveground biomass components were calculated by a nonlinear and a linear fitting approach. The study showed that coarse root biomass of mountain birch was almost exclusively (> 95 weight-%) located in the top 30 cm, even in a natural old-growth woodland. By using a cross-validation approach, we found that the nonlinear fitting procedure performed better than the linear approach with respect to predictive power. In addition, our results underscore that general assumptions of fixed conversion factors lead to an underestimation of the belowground biomass. Thus, our results provide allometric functions for a more accurate root biomass estimation to be utilized in inventory reports and ecological studies.

Keywords: mountain birch, belowground biomass, root depth distribution, aboveground biomass, *Betula pubescens Ehrh. ssp. czerepanovii*

YFIRLIT
Lífmassaföll og dýptardreifing grófróta birkis á Suðurlandi
Rótarkerfi trjáa innihalda umtalsverðan lífmassa og traust mat á honum skiptir máli til dæmis þegar kolefnisforði skóga er metinn. Langflestar rannsóknir á trjáa lífmassaföllum (spálíkön út frá bolþvermáli) hér og erlendis hafa hinsvegar einskorðast við ofanjarðarlífmassa þeirra. Þegar reynt hefur verið að áætla rótarlífmassa hefur hann yfirleitt verið metinn sem fast hlutfall af ofanjarðarlífmassa. Í þessari rannsókn voru 25 birkitré á mismunandi aldri (bolþvermál þeirra í 50 cm frá jörðu var 0,2 – 14,1 cm) uppskorin á Rangárvöllum. Allt rótarkerfi þeirra var grafið upp og þvermál róta og dýptardreifing ákvörðuð. Lífmassaföll voru síðan reiknuð fyrir magn grófróta (> 5 og 2 mm), rótarháls (stubb), heildarlífmassa rótarkerfis og ofanjarðarlífmassa

með ólínulegu aðhvarfi. Niðurstöðurnar sýndu að nánast allan rótarlífmassa birkis (> 95%) var að finna í efstu 30 cm jarðvegs. Ólínulegu lífmassaföllin lýstu vel hvernig rótarlífmassi breyttist með aldri og ennfremur að það að meta hann sem fast hlutfall af ofanjarðarlífmassa leiðir til umtalsverðs vanmats á honum. Þessar niðurstöður geta því nýst vel þegar rótarlífmassi birkis er metinn fyrir kolefnisúttektir og aðrar vistfræðilegar rannsóknir.

INTRODUCTION

Mountain birch (*Betula pubescens Ehrh. ssp. czerepanovii*), a subspecies of downy birch, commonly forms the altitudinal treeline in Scandinavia (Carlsson et al. 1999, Väre 2001, Wielgolaski et al. 2005). It also forms the dominant forest type north of the coniferous boreal forest in the subarctic region (northern Fennoscandia and north-western Siberia) and is also present in the subalpine areas of Scotland (Väre 2001, Wielgolaski et al. 2005). Mountain birch is also the dominant tree species in the native woodlands of SW Greenland and Iceland (Aas & Faarlund 2001, Normand et al. 2013). Morphologically the species can grow monocormous (single-stemmed) or polycormous (multi-stemmed) (Verwijst 1988, Bylund & Nordell 2001).

There has been a large-scale increase in mountain birch growth in the Scandinavian mountains and in Iceland in recent decades, most likely driven by changes in land use and climate (Tømmervik et al. 2004, Wöll 2008). Besides various ecological consequences of large-scale changes in the extent of birch areas, they can potentially affect the greenhouse-gas (GHG) balance of the region. Forest carbon sinks were included in the Kyoto Protocol as one of the mechanisms for mitigating climate change, since these sinks are known to play an important role in the global carbon balance (Ciais et al. 2013). Reliable estimates of changes in biomass carbon stocks, both aboveground and belowground, are thus crucial for understanding and quantifying the contribution of forest growth to regional and national carbon balances.

In general, estimates of national carbon stocks and stock changes in temperate and boreal forests have been based on national forest inventory data which have been available for Iceland since 2001 (Snorrason 2010a, Tomppo et al. 2010). The aboveground stock estimations for mountain birch in the Icelandic national forest inventory (IFI) are based on biomass functions (Snorrason & Einarsson 2006, Snorrason 2010a). Belowground stocks (root stock and coarse roots > 2mm) are estimated by the root:shoot ratio of 0.25 (Snorrason et al. 2002, Snorrason & Einarsson 2006, Snorrason 2010b). A single root:shoot ratio for belowground biomass estimates is used due to a lack of better and standardized methods because of the little known information about the root systems (Brown, 2002). Such ratios are usually based on large-scale (ecosystem or even biome scale) studies (Stone & Kalisz 1991, Vogt et al. 1996, Jackson et al. 1996, Cairns et al. 1997). However, the review of Mokany et al. (2006) and an Icelandic study (Snorrason et al. 2002) provide evidence that the root:shoot ratio is age and species dependent and needs an additional model to estimate the shoot biomass stock which already is subject to uncertainty. Thus, to reduce uncertainties in estimates of belowground biomass stock, allometric equations for the belowground biomass pool are urgently required (Brown 2002).

Allometric functions for above- and belowground parts of mountain birch are available for Fennoscandia (Sveinbjörnsson 1987, Starr et al. 1998, Bylund & Nordell 2001, Dahlberg et al. 2004, Bollandsås et al. 2009) and Iceland (Sigurðardottir 2000, Snorrason & Einarsson 2006). The Icelandic studies in detail, Snorrason & Einarsson (2006) published allometric functions for the stem and total aboveground components of mountain birch together with mountain ash (*Sorbus aucuparia*) based on a countrywide dataset and Sigurdardottir (2000) developed functions for above- and belowground biomass pools of 65-year-old naturally regenerated mountain birch trees located in eastern Iceland.

Due to cost and time efficiency, root systems have mostly been excavated without any documentation of the root system architecture (Sigurðardottir 2000, Snorrason et al. 2002). However, roots play a key role in soil formation processes and nutrient cycles (Jenny 1994, Gregory 2006), especially in disturbed landscapes that have undergone restoration and afforestation activities as in Iceland (Aradóttir & Arnalds 2001, Aradóttir 2007). Hence, in addition to the amount of root biomass, knowledge of the distribution of the belowground biomass is required with respect to the carbon sequestration potential, for example of the mountain birch ecosystem. However, information on the development of mountain birch root systems is sparse and only Anschlag et al. (2008) studied the maximal rooting depth of mountain birch seedlings in north Finland.

With this background in view the aims of the present study were to derive allometric relationships for both above- and belowground woody biomass of mountain birch in southern Iceland by testing two fitting approaches and comparing the resulting functions with existing ones. The study material included smaller trees than have been included in earlier studies (Sigurðardottir 2000, Snorrason & Einarsson 2006). This is important considering the effect of establishing woodlands on ecosystem biomass stocks. In contrast to other publications this study also emphasized the vertical distribution of different sized roots.

MATERIALS AND METHODS

Study area

The study area is in the vicinity of the volcano Mount Hekla (Figure 1). Due to unsustainable land use and volcanic activity in Mount Hekla, most of this area is now affected by erosion (Aradóttir 2007). To combat the ongoing land degradation and soil erosion a large-scale project, *Hekluskógar*, was established in 2007 with the aim of restoring birch woodlands on ca. 900 km^2 in the vicinity of Mount Hekla (Aradóttir 2007). To study the ecological impact of such restoration, the research project *CarbBirch* was started in 2008 (Halldórsson et al. 2009). The present study was a part of the *CarbBirch* project and used two of the five study sites of *CarbBirch*. The study material was collected at three sites (Figure 1), which represented two different aged plantations (B_1 and B_2 at Bolholt) and nearby remnants of mountain birch (*Betula pubescens Ehrh. ssp. czerepanovii*) woodland, which earlier covered large areas in the vicinity of Mount Hekla (Árnason 1958) (B_3 at Hraunteigur). B_3 is located on a narrow ness between two streams that protected it from the approaching sand dunes. The woodland at Hraunteigur is relatively low in stature, similar to the majority of Icelandic birch woodlands (Jónsson 2004), but perhaps not representative of taller birch forests found in a few places (Traustason & Snorrason 2008). Because of the long term continuous vegetation cover, this area has accumulated thick soils with a soil depth of more than > 2 m (Helgason 1899, Kolka 2011). More detailed stand data are shown in Table 2.

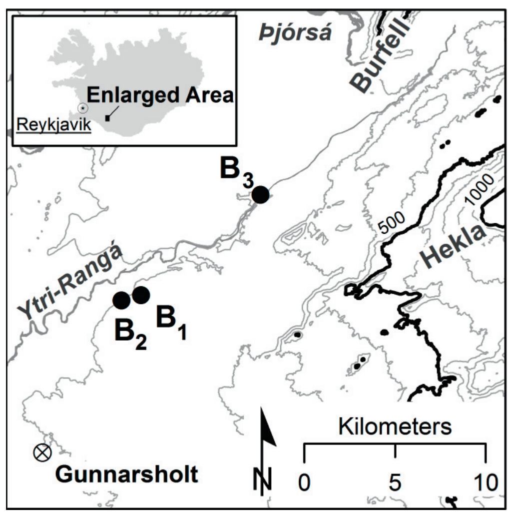

Figure 1. Topological map (equidistance = 100 m) showing the three study sites (filled circles) and Gunnarsholt (crossed circle), headquarters of the Icelandic Soil Conservation Service (SCS), in South Iceland.

Table 1. Ecological characteristics of the study sites in southern Iceland sampled in 2009. The variables are type of forest (Type), elevation above sea level (Elev.; m), mean annual temperature (T_{mean}; °C) and annual precipitation (P_{sum}; mm) from an interpolated temperature normal (Bjornsson et al. 2007) (T_{mean} and P_{sum} of >0 °C threshold, respectively), bedrock and soil type.

Site	Type	Elev.	T_{mean}	P_{sum}	Bedrock	Soil type
B_1	planted	125	3.5	1721	Lava	Vitric Andosol, coarse grained
B_2	planted	93	3.6	1701	Lava	Vitric Andosol, coarse grained
B_3	natural	90	3.5	1640	Lava	Vitric Andosol, with coarse tephra layers in between.

All three study sites were located on basaltic lava bedrock covered with tephra and aeolian deposits. In each case the soil type was a Vitric Andosol (Arnalds 2004). All three sites featured a similar elevation and climate (Table 1).

Stand inventory
The study sites represented different stages in ecosystem succession of mountain birch that is now found in the Hekluskógar area. A tree inventory was conducted at each site in July and August 2009 by systematically placing four circular plots near a 200 m^2 *CarbBirch* study area from which the trees were later harvested (see section *Harvesting*). At each plot, the stem length for each tree, stem diameter at ground level, 50 cm and 130 cm length and dominant height were measured. Stem length and dominant height are not equal when trees are not straight; the former is used for allometric calculations whereas the latter is used to describe the stature of the forest. During inventory measurements, a total of 27 tree ring cores were collected with an increment borer from trees of the highest and the median diameter class.

Tree ring countings
Tree ring measurements were conducted on the 27 tree ring cores (54 radii measurements) by using LINTAB measurement equipment (Frank Rinn, Heidelberg, Germany) fitted with a Leica MS5 stereomicroscope, and analysed with the TSAPWin software. The ring width series were plotted and visually synchronized for identification of errors during the measurements (Fritts 1976, Schweingruber 1996).

Harvesting
Altogether 25 monocormic trees with a length > 50 cm were randomly selected at sites B_1, B_2 and B_3. After felling at ground level (Tomppo et al. 2010), stem, branches and the fully developed foliage were separated and put in paper bags. The belowground biomass (root stock and coarse roots) was then carefully excavated and put in paper bags. According to the COST Action E43 Reference Definition Nr. 47 coarse roots > 2 mm were harvested (Tomppo et al. 2010). During the excavation of the whole root system, the biomass was immediately categorized by size (root stock, > 50 mm, 50 – 10 mm, 10 – 5 mm, 5 – 2 mm) and the vertical root distribution was defined by soil depth classes (0 – 10 cm, 10 – 20 cm, 20 – 30 cm, 30 – 50 cm, 50 – 70 cm, 70 – 100 cm). Due to the oval cross sectional area at the intersect of root stock and roots, the outgoing roots were categorized by taking the average of their minimum and maximum diameter at the intersect.

Laboratory work
The different components of the biomass were dried separately at 85 °C until daily weight loss was less than 1 percent. To accelerate the drying process big stumps and stems were sawn up into disks with a power saw. The disks and the sawdust were dried in the same conditions. The accuracy of the measurement of the weight was 0.01 g.

Allometric relationships and biomass stock estimations

To find the best fitted allometric coefficient (*a*) and allometric exponent (*b*) and the corresponding confidence intervals (95% CI) non-linear (NLR) and linear (LR) regression approaches were applied (Lai et al. 2013). For this, the common power function (Eq. 1) and its ln-transformed type (Eq. 2) were used. *D* as the stem diameter (cm) at 50 cm length and *DM* as the weight of the dry biomass (kg) of each component of the 25 harvested trees were then used as dependent and independent variables, respectively.

$$DM = a \times D^b \quad \text{(Eq. 1)}$$

$$\ln(DM) = \ln(a) + b \times \ln(D) \quad \text{(Eq. 2)}$$

The analysis was implemented in the MATLAB R2011b and the Statistics Toolbox, using the functions *nlinfit* for NLR and *LinearModel.fit* for LR. In order to diminish the influence of increasing variability with size, a robust algorithm that employs an iteratively reweighting least-squares scheme was chosen. The *fair* function was used as the weighing function (MathWorks, Inc. 2011b). The bias, which occurs during the back-transformation from logarithmic to arithmetic scale, was corrected by the correction factor (CF) (Baskerville 1972, Sprugel 1983). To validate the NLR and LR models a leave-one-out cross-validation (LOOCV) was applied. Cross-validated residuals were subsequently used to calculate the mean relative prediction error (RPE [%]) of the model as a measure of the predictive precision. The corrected Akaike information criterion (AICc) was computed for each model as the second statistical parameter. The AICc incorporates both the likelihood of the model and a penalty of extra parameters measuring the goodness of fit of a statistical model (Burnham & Anderson 2002, Lai et al. 2013). In a following step the growing woody biomasses for the aboveground and belowground (> 2 mm) components at the three sites were estimated. For this, the chosen equations were applied to the inventory data by using the measured diameter of each stem within the inventoried plot as the independent variable.

Comparison with other equations

The allometric equations for the stem and the coarse root biomasses were compared to existing functions. However, due to the use of D_0 as the independent variable in Bylund & Norell (2001) and D_{130} as the independent variable in Starr et al. (1998), Sigurdardottir (2000), Dahlberg et al. (2004) and Bollandsås et al. (2009) the potential diameter at 50 cm length (D_{50_0} and D_{50_130}) was first estimated based on the inventory data of the present study. For these relations two linear regressions were used (Eq. 3 and Eq. 4) (data not shown) where D_0, D_{50} and D_{130} represent the diameters at 0, 50 and 130 cm length of the living birch trees. The equations include the 95% confidence intervals for the coefficients.

$$D_{50\_0} = 0.66 \pm 0.03 \times D_0 - 0.13 \pm 0.26$$

n=402 and R^2=0.81 (Eq. 3)

$$D_{50\_130} = 1.09 \pm 0.03 \times D_{130} + 1.21 \pm 0.13$$

n=402 and R^2=0.92 (Eq. 4)

Vertical distribution of the coarse root biomass

In addition, we plotted the belowground biomass of B_1, B_2 and B_3 categorized by root thickness and vertical distribution. Further, to compare the data with already existing values (Jackson et al. 1996) the root depth extinction coefficients (β) were calculated by the formula of Gale & Grigal (1987), where DM_r is the cumulative root fraction [%] in a certain soil layer (d; cm).

$$\beta = \left(1 - \frac{DM_r}{100}\right)^{1/d} \quad \text{(Eq. 5)}$$

Table 2. Stand characteristics. Age (range of tree ages; years), mean diameter at 50 (D_{50}; cm) and at 130 cm stem length (D_{130}; cm), dominant height (H_d; m), stand density (Dens.; number of stems ha^{-1}) and basal area at 130 cm stem length (BA; m^2 ha^{-1}) of the study sites in southern Iceland. In parentheses is the standard deviation, based on 4 sample plots. Within-column values marked with different letters are significantly (Mann-Whitney U Test; $p < 0.05$) different.

Site	Age	D_{50}	D_{130}	H_d	Dens.	BA
B_1	5 – 12	1.4 (0.9)^a	0.4 (0.6)^a	2.3 (0.2)^a	9563 (1652)^a	0.4 (0.1)^a
B_2	7 – 20	3.8 (1.4)^b	2.2 (1.2)^b	3.2 (0.1)^b	7171 (2715)^a	3.5 (1.6)^b
B_3	73 – 82	7.9 (3.4)^c	6.2 (3.2)^c	4.8 (0.2)^c	4038 (970)^b	15.2 (2.8)^c

RESULTS

Sample site characteristics

The three sites used in the present study were chosen because they had mountain birch trees of different age and size (Table 2). The mean tree age, as determined by annual ring counts, was 9, 14 and 78 year for sites B_1 – B_3, respectively. Similarly, the dominant height, the diameters at 50 cm length and breast height (D_{130}) and the basal area also increased with age. The stand density however showed an age-related decline (Table 2).

Allometric relationships and biomass stock estimations

The outcome of the allometric analysis is given in Table 3. The models derived from the NLR approach mostly predicted more accurately and with a lower variation than those from the LR approach. Furthermore, the negative Δ AIC_c values indicated that the NLR models supported the data better. Neither approach was favoured over the other for the leaf and root (> 5 mm) components.

The living aboveground and belowground biomass stocks for the three stands were calculated with the NLR approach. The estimations predicted that at B_2 the stock already stored about 30% of B_3's stock. Further, with the approach used to estimate the growing biomass stock, the maximum stock was about 68 t ha^{-1}. The ratio between the belowground biomass and the total biomass was about 0.3 for the three sites (Table 4).

Comparison with other equations

The estimated stem biomass (Figure 2; A) based on published functions showed that the results of the present study were well comparable with the estimations based on Sigurðardottir (2000) (stem and bark biomass). However, the stem function of the present study estimated a slightly higher biomass than Snorrason & Einarsson (2006). Generally the stem function of the present study predicted stem biomass which is within the range of those of the already existing functions from the Fennoscandian region.

Focusing on the belowground biomass (Figure 2; B), the comparison between all three existing studies generally showed that the differences in the results between these studies are higher than for the stem biomass estimations. Further, biomass estimations based on root:shoot ratios (Snorrason & Einarsson 2006) underestimate the belowground component of Icelandic mountain birch compared to the function of the present study and Sigurdardottir (2000).

Vertical distribution of coarse root biomass

The analysis of the root biomass showed an increase in the root depth extinction coefficient (β) which was 0.797 at B_1, 0.829 at B_2 and 0.900 at B_3. In more detail, at all three sites more biomass was accumulated in the thicker roots in the upper sampling horizons and smaller roots only dominated in the deeper sampling horizons (Figure 3). Further, at the

Table 3. Comparison of the nonlinear (NLR) and linear (LR) regression approach. Given are the estimated function parameters (a and b) and the corresponding 95% confidence intervals (CI), the arithmetic mean (Ø) and the standard deviation (σ) of the relative prediction errors (RPE, %), the correction factors (CF) for the LR models and the difference of the AIC_c ($\Delta AIC_c = AIC_{cNLR} - AIC_{cLR}$) for the different biomass components. The models use diameter at 50 cm stem length as an independent variable (D_{50} = 0.2 – 14.1 cm).

Components	NLR			LR				Δ AIC_c	N
	Parameter estimates		RPE	Parameter estimates		RPE	CF		
	a (CI)	b (CI)	Ø (σ)	a (CI)	b (CI)	Ø (σ)			
Roots (> 2 mm)	0.029 (-0.005, 0.063)	2.127 (1.672, 2.582)	46.2 (28.3)	0.060 (0.047, 0.077)	1.729 (1.546, 1.911)	59.9 (67.0)	1.16	-7.3	25
Roots (> 5 mm)	0.019 (-0.003, 0.041)	2.220 (1.770, 2.670)	56.5 (54.3)	0.033 (0.027, 0.042)	2.002 (1.834, 2.170)	73.5 (118.7)	1.22	-0.1	25
Root stock	0.004 (0.002, 0.006)	2.717 (2.510, 2.924)	73.3 (22.2)	0.034 (0.025, 0.046)	1.639 (1.405, 1.874)	87.7 (76.7)	1.29	-13.1	25
Belowground (> 2 mm)	0.034 (0.008, 0.060)	2.293 (2.002, 2.585)	46.7 (29.3)	0.094 (0.072, 0.122)	1.701 (1.502, 1.899)	62.5 (57.4)	1.18	-18.8	25
Belowground (> 5 mm)	0.027 (0.009, 0.045)	2.341 (2.085, 2.597)	45.1 (28.5)	0.068 (0.051, 0.089)	1.803 (1.597, 2.009)	67.3 (67.1)	1.20	-19.0	25
Stem	0.021 (0.010, 0.032)	2.638 (2.434, 2.842)	54.2 (31.9)	0.084 (0.067, 0.104)	1.802 (1.638, 1.966)	49.4 (27.3)	1.12	-29.6	25
Branches	0.019 (-0.004, 0.042)	2.591 (2.135, 3.048)	46.6 (31.5)	0.064 (0.046, 0.089)	1.915 (1.663, 2.166)	95.8 (101.6)	1.31	-12.2	25
Leaves	0.057 (0.045, 0.068)	1.322 (1.243, 1.402)	35.6 (33.8)	0.059 (0.050, 0.071)	1.282 (1.149, 1.416)	37.4 (39.9)	1.08	0.4	25
Aboveground	0.071 (0.027, 0.114)	2.361 (2.121, 2.601)	43.1 (33.3)	0.218 (0.168, 0.283)	1.732 (1.536, 1.928)	60.6 (43.3)	1.17	-22.9	25
Total biomass	0.106 (0.038, 0.174)	2.336 (2.086, 2.585)	43.3 (31.8)	0.311 (0.241, 0.403)	1.723 (1.529, 1.917)	59.9 (45.6)	1.17	-22.6	25

Table 4. Aboveground and belowground (> 2 mm) biomass stocks (t ha^{-1}) of mountain birch at the three test sites estimated by allometric functions and the inventory data based on 4 sample plots. The root:shoot ratios (R:S ratio) and the portion of the belowground to total tree biomass (RMR) are listed based on the 25 sampled trees. The table shows mean and standard deviation (in parenthesis) values. Within-column values marked with different letters are significantly (Mann-Whitney U Test; $p < 0.05$) different.

Site	Aboveground [t ha^{-1}]	Belowground [t ha^{-1}]	R:S Ratio [-]	RMR [-]
B_1	2.6 (1.0)[a]	1.2 (0.4)[a]	0.45 (0.08)[a]	0.31 (0.04)[a]
B_2	15.1 (5.7)[b]	6.6 (2.5)[b]	0.39 (0.05)[a]	0.28 (0.02)[a]
B_3	47.5 (6.9)[c]	20.8 (3.1)[c]	0.37 (0.05)[a]	0.27 (0.02)[a]

stand B_3 than at B_2. At B_3 the root systems vertically penetrated down to 100 cm soil depth and stored biomass material in all recorded root categories.

DISCUSSION

Allometric relationships and biomass stock estimations

The methods used in the present study make it possible to derive biomass and carbon stocks for smaller diameter trees (0.2 – 14.1 cm at 50 cm stem length) than was earlier possible (Sigurðardottir 2000,

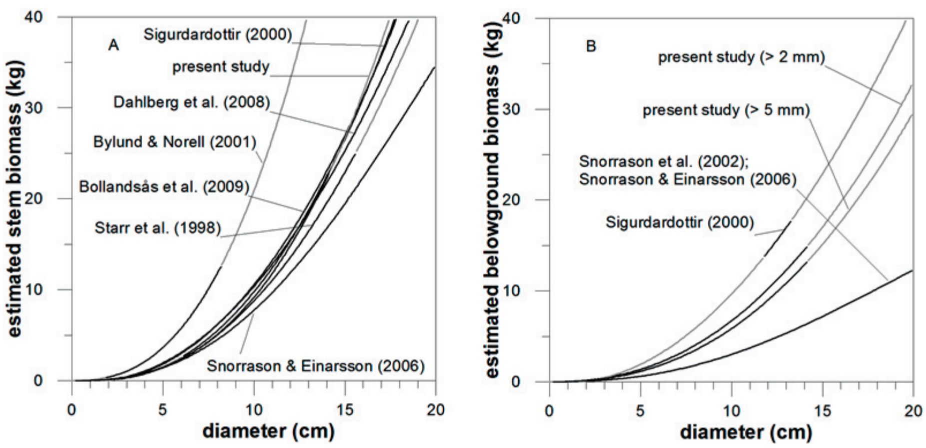

Figure 2. Predicted stem biomass (A) and belowground biomass (B) by existing allometric functions for mountain birch. The functions of the present study are modeled with the NLR approach. The responsible diameter ranges are indicated by black lines.

plantation sites B_1 and B_2 the roots had a maximum penetration depth of 70 cm and had a diameter smaller than 50 mm (Figure 3). Between these two sites, which had only a 5 year difference in average age, a threefold increase in the root biomass was observed in the top 20 cm. Additionally the thickening of the root system in the top 10 cm caused an increase within the root-thickness category 50-10 mm by a factor of 5.8 (Figure 3). However, about 310 times more biomass was stored in the root systems at the natural old grown

Snorrason & Einarsson 2006). It also presents new equations for foliage and, most importantly, for coarse roots that have not been included in earlier publications from Iceland. These can be of use for various ecological studies in Iceland and for national inventory reports like the National Forest Inventory or the National Inventory Report for greenhouse gases (Hallsdóttir et al. 2013, Snorrason 2010a).

Comparing the two chosen fitting approaches, the estimated parameters of the power function (Eq. 1) had obviously wider confidence

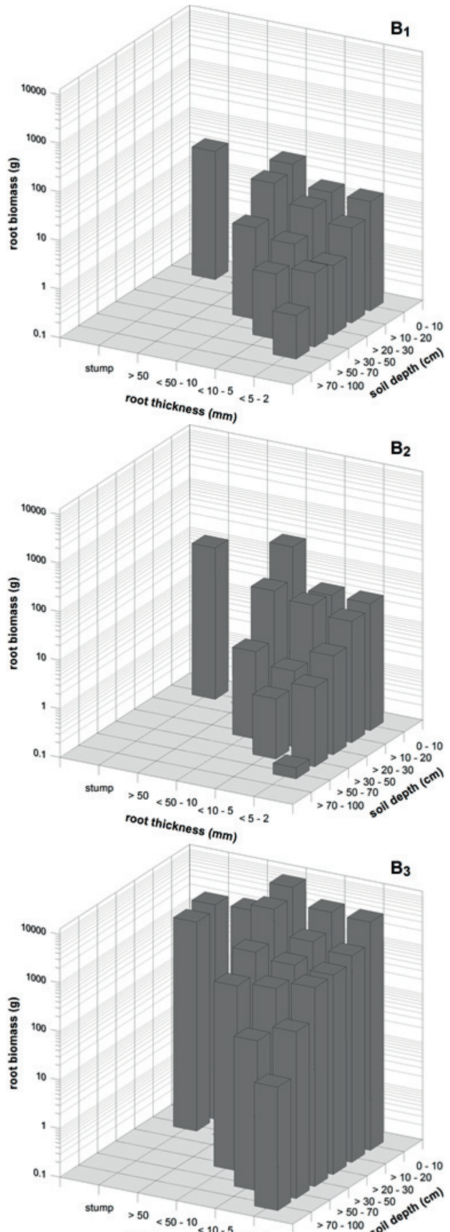

Figure 3. Mean biomass stocks (dry weight) of the excavated root systems categorized by root size and depth layer for B_1, B_2 and B_3. Root stock biomass is categorized as *stump*. Note that biomass stocks are plotted logarithmically.

intervals than those of the logarithmic function (Eq. 2). This can be explained by the reduction in the least squares during the transformation of the data using the LR approach. Furthermore, the statistical parameters (RPE and Δ AIC_c) showed that the equations derived with the NLR method are mostly favoured (Lai et al. 2013). According to the RPE values of both approaches (Table 3), the biomass estimations are coupled with relative prediction errors which mostly have higher variations with the LR approach. Besides, the RPE values of both approaches are heteroscedastic but the values derived from the LR approach show a higher variation for smaller stem diameters. Due to these findings, the use of the NLR approach is favoured to estimate the living woody biomass of both young plantations and old-growth woodlands.

The estimate of aboveground biomass stocks (Table 4) is in accordance with data published by Snorrason et al. (2002). Sigurdardottir (2000) calculated a higher living aboveground biomass (55 t ha^{-1}), which can be explained by the different stature of the trees in eastern Iceland (e.g. dominant height: 8.8 m). Starr et al. (1998) and Bylund & Nordell (2001) reported, however, lower stocks for sites in north Finland (21.2 t ha^{-1}) and north Sweden (9.6 t ha^{-1}), respectively. However, mountain birch woodlands in north Scandinavia are often growing on marginal land and are subject to large mammal grazing (c.f. Tømmervik et al. 2004), which is not the case for Icelandic birch woodlands, which may explain the difference in biomass stocks. With regard to the belowground woody biomass, the stock in an old-growth woodland was 20.8 ± 3.1 t ha^{-1} (Table 4). This is relatively high compared to a 54-year-old woodland (about 10 t ha^{-1}) (Snorrason et al. 2002), but lower than was reported for a 65-year-old birch woodland 39.2 ± 5.1 t ha^{-1} by Sigurdardottir (2000). The two plantation sites B_1 and B_2 stored the lowest stocks (Table 4). Generally, about one third of the total woody biomass was stored in the root stock and the coarse root components (Table 4). These are higher amounts than found by Snorrason et al. (2002).

It has to be mentioned that when using the allometric functions of the present study to estimate the belowground biomass stock of the different stands we made one important assumption; we assumed no differences in the relationship between stem diameter and root biomass between monocormic and polycormic trees that indeed occurred within the inventory plots. Addressing this issue by harvesting polycormic trees of similar size classes and redoing the allometric analysis where this factor would be taken into account is of high priority. This is, however, not a unique shortcoming for the present study, since basically all previous root allometric relationships for *Betula* sp. have only included monocormic trees (Sigurðardottir 2000, Petersson & Ståhl 2006). Hence, basically all studies that use published allometric relationships to estimate root biomass have made the same assumption. At the moment it is unclear whether this leads to an overestimation or underestimation of the belowground biomass stock.

Comparison with other equations

Previous studies on allometry of mountain birch in Iceland have focused on somewhat larger trees (Sigurðardottir 2000, Snorrason & Einarsson 2006). Snorrason & Einarsson (2006) used both diameter and height as independent variables for their biomass equations. Their equations are valid for the diameter range of 2.1 – 29.8 cm (D_{50}) and estimate stem volume, stem biomass and total aboveground biomass of both mountain birch and mountain ash (rowan). These equations are now used for the National Forest Inventory of Iceland (Snorrason 2010a). Another study (Sigurðardottir 2000) determined equations for stem wood, stem bark and branches with a diameter range of 6.1 – 21.2 cm (D_{130}) and roots > 5 mm with a diameter range of 11.7 – 13.3 cm (D_{130}).

The equation for the stem biomass of the present study is well comparable with the already existing functions (Figure 2; A). However, site conditions influence the growth pattern and therefore also the biomass accumulation and distribution, respectively (Weih & Karlsson 2001, Schenk & Jackson 2002). Besides this, different harvesting techniques and accuracy may also increase the variation in the allometric functions, especially for the belowground biomass components. For the belowground part the present study modelled allometric functions for coarse roots > 5 mm and > 2mm. The two equations fall between the functions of Sigurdardottir (2000) and Snorrason & Einarsson (2006). The reasons for showing the functions for both root size definitions are, on the one hand, for comparison to already existing studies focused on roots > 5mm (Sigurðardottir 2000) and on the other hand, the long-term agreement of COST Action E43 and that the Icelandic Forest Research Station define coarse roots as biomass > 2 mm in diameter. Thus the present study provides the required allometric function for coarse roots > 2 mm. Further, the comparison shows that an estimation of the belowground biomass at tree level based on a function for total aboveground biomass and a root:shoot ratio of 0.25 (Snorrason 2010b) leads to an underestimation of the coarse root biomass compared to the two other studies (Figure 2; B).

Estimation of belowground biomass

By using the allometric functions (Table 3), the coarse root biomass fraction (root stock excluded) changed with tree size in the present study. It was 38% of the total biomass when diameter at 50 cm length was 0.2 cm and had decreased to 16% when the diameter had reached 14 cm. The total belowground biomass fraction (root stock included) changed from 40% to 26% within the same diameter range. This finding agrees with the already published data of Monkany et al. (2006) and Sveinbjörnsson (1987). Sigurdardottir (2000) found that the coarse root biomass was 34% of the total biomass in a 60-year-old stand.

Snorrason et al. (2002) also excavated a few mountain birch root systems in a 54-year-old plantation, close to where the present study took place. They did not attempt to make any allometric relationships, but found that the root systems of mountain birch on average contained 20% of the total tree biomass. Compared to this study, the present study showed higher RMR values on tree level for all three test sites (Table 4). Applying the country specific root:shoot ratio of 0.25 (Snorrason, 2010b), which describes the relationship between aboveground and belowground biomass, the mean belowground biomass of the harvested trees is underestimated at the test sites by 42% (B_1), 35% (B_2) and 31% (B_3). Thus, with regard to the high variability of the root:shoot ratio and the large increase in newly afforested areas in Iceland (Sigurdsson et al. 2007), which may cause a higher root:shoot ratio of the corresponding young stands (Table 4), the use of a more accurate method like the allometric approach would be advisable.

Vertical distribution of coarse roots

Digging up the whole root system requires motivation and time. However, with an applied destructive method we got a good knowledge about the morphology of the mountain birch root systems.

In the present study, the increase in the root biomass between B_1 and B_2 mainly took place in the top 20 cm of soil (Figure 3). Curt & Prévosto (2003) studied the root profiles of silver birch (*Betula pendula*) and found similar growth patterns in trees about 30 years old. The reason for the more intense development of lateral roots compared to taproots for young trees of *Betula pubescens* may be explained as an adaptational strategy for maximal nutrient acquisition in absence of water stress (Einarsson 2013). Birch as a pioneer plant (Kutschera & Lichtenegger 2002) takes its resources from the topsoil, which is mainly affected by weathering processes in initial soils (Hutchings & John 2003).

It should be noted that there may be an inherent difference in the root systems of the young, planted sites of B_1 and B_2 and the Hraunteigur site (B_3). The latter represented an old-growth birch woodland that is known to have existed in 1898 (Helgason 1899), before the stems included in the present study started to grow. Mountain birch woodlands can regenerate from seeding or from basal sprouts that grow from older root systems (Aradóttir & Arnalds 2001, Aradóttir et al. 2001). Therefore, the root systems of B_3 may partly be older than the annual rings of their currently existing stems would indicate. This should be kept in mind when the present data are used. Nevertheless, the whole root system should be considered with respect to both biomass and carbon accumulation.

A review of root distribution for terrestrial biomes by Jackson et al. (1996) concluded that 83% and 93% of the root biomass is stored in the top 30 cm of the soil for typical plant species of the boreal and tundra biome, respectively. Hence, root biomass tends to be located in deeper soil layers in boreal ecosystems. This is also indicated by lower root depth extinction coefficients (β) for boreal plants ($\beta = 0.943$) compared to that for tundra plants ($\beta = 0.914$). The B_3 site, which was an old-growth woodland, showed a closer approximation to the tundra extinction coefficient and had a high β-value ($\beta = 0.900$) compared to the two values from the literature. Hence, the old-growth mountain birch woodland (B_3) stored an equal amount of root biomass (95%) in the top 30 cm as typical plant species in the tundra biome. However, the comparison is difficult. Fennoscandian mountain birch woodlands are part of the so-called subarctic forest (Wielgolaski et al. 2005). It is an ecotone that represents the transition zone between the predominantly coniferous boreal and the treeless tundra biomes. This might be the reason for why mountain birch as a species is not listed in any of the mentioned biomes.

Rooting depth

The present study did not measure the maximal rooting depth, since only coarse roots were measured. However, Figure 5 shows that at B_1 and B_2 the maximal rooting depth of coarse roots was between 50 and 70 cm at both sites. Further, at B_3 some few taproots (> 2 mm) penetrated several tephra layers and reached a depth of about 1 m. Polunin (1933, 1937) analysed vertical extension of birch root systems in Lapland and Greenland in the 1930s. Rooting depth of downy birch in northern Lapland was more than 2 m, while in Greenland rootlets of *Betula pubescens* sens. lat. penetrated between 1 and 2 m. Similar findings were observed for the penetration depth of coarse roots at B_3. Canadell et al. (1996) reviewed maximal rooting depth for several biomes, where boreal forests and tundra had a mean root penetration depth of about 2.0 m and 0.5 m, respectively.

It is concluded that the unique Icelandic soil conditions call for country specific allometric functions for mountain birch instead of those based on large-scale biome reviews or adapted from the Fennoscandian region. Additionally our study shows that for belowground biomass stock calculations over a wide diameter range, allometric functions should be used instead of a constant root:shoot ratio. Independently of the tree age, almost the whole root system of mountain birch was stored in the top 30 cm, which is an unexpected result for a sub-arctic tree species and has to be taken into account in biomass and carbon inventories and studies on soil forming, ecosystem and carbon cycling processes, respectively. The samples used for the present study were taken in South Iceland and may thus only be representative of results for this particular region. We conclude that there is further need to test and derive allometric relationships, especially for belowground components, based on a countrywide dataset consisting of polycormic as well as monocormic trees.

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