

Belowground biomass models for young oligotrophic Scots pine stands in Latvia

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The increasing interest in carbon budget estimation and the growing use of woody biomass in bioenergy production raises the necessity for precise estimates of belowground biomass and soil carbon pools in forest ecosystems, particularly in terms of changes in the age structure of forests. The aim of this study was to estimate the belowground biomass of young (< 40 years) stands of Scots pine (*Pinus sylvestris* L.) in Latvia. The biomass of small roots (diameter 2-20 mm), coarse roots (diameter > 20 mm), and stumps of 39 trees from eight stands growing on dry, nutrient-poor mineral soils was measured and compared to the aboveground variables of sampled trees. The results revealed that stumps, small roots, and coarse roots comprised 43%, 35% and 22%, respectively, of the belowground biomass of young Scots pines. The proportion of belowground biomass over the total tree biomass was age-dependent, ranging from 33% to 17% for 8-year and 40-year old trees, respectively. Aboveground tree variables were significantly correlated with the belowground biomass, being stemwood volume and basal area the best predictors ($R^2 = 0.86-0.98$, relative errors = 26-43%) of the belowground biomass components. Accordingly, the developed models produced more accurate estimates compared to previous models for the region, thus reducing the uncertainty in determining the carbon budget for belowground biomass. Still, an analysis of a more comprehensive dataset is needed to account for the effect of the social status of trees, as well as the within- and between-stand variation.

Keywords: Hemiboreal Forests, Europe, *Pinus sylvestris*, Allometric Equation, Coarse Roots, Total Root Biomass

Introduction

The increasing international efforts aimed at mitigating climate change have raised interest in forest biomass for bioenergy production (Sochacki et al. 2017), and highlighted the role of forest biomass in carbon (C) cycling (Brunner & Godbold 2007, Thomas & Martin 2012). Many studies have recognized the importance of large-scale, as well as stand-level factors in determining the dynamics of forest biomass (Vanninen et al. 1996, Makkonen & Helmisaari 2001), particularly in boreal forests, which represent one of the largest C pools in the world (Finér et al. 2011).

Belowground biomass accounts for 18-45% of the total tree biomass in coniferous stands (Fogel 1983, Cairns et al. 1997, Lit-

ton et al. 2003), indicating a large variability and uncertainty in belowground C estimations (Finér et al. 2011, Addo-Danso et al. 2016). The root system consists of various components which are difficult to be directly estimated, despite their vital role in the development and functioning of trees (Makkonen & Helmisaari 1998, Ohashi et al. 2007). Numerous field methods and allometric models for the estimation of aboveground biomass have been previously published (Sanford & Cuevas 1996, Neumann et al. 2016). Contrastingly, the development of accurate methods for quantifying belowground biomass has lagged behind, primarily due to methodological challenges and the laborious and costly collection of empirical data on heterogeneous root sys-

tems (Brassard et al. 2011, Varik et al. 2013, López-Serrano et al. 2015).

Many factors, such as location (climate), species, age, forest type, and soil oxygen and moisture regime, influence the development of root system of trees (Makkonen & Helmisaari 1998, Dieter & Elsasser 2002, Finér et al. 2007). Accordingly, the need to develop local, site-based belowground biomass models for various tree species has been recognized throughout Europe (Zianis et al. 2005, Muukkonen & Mäkipää 2006). Emphasis has been placed on the extension of models across different species, in order to predict belowground biomass using easy-to-measure aboveground variables of trees (Chakraborty et al. 2016, Neumann et al. 2016).

Scots pine (*Pinus sylvestris* L.) is one of the main tree species in the Eurasian boreal and boreo-nemoral zone, representing about 20% of northern forests (Hyttborn et al. 2005). In Europe, it is an economically important species that can withstand various weather extremes (Dieter & Elsasser 2002). Whilst numerous studies on Scots pine biomass have been conducted in Fennoscandia (Finér et al. 2007, Repola 2009), studies on belowground biomass of Scots pine in the Baltic region are scarce, though some results have been recently published (Bardulis et al. 2012, Liepins et al. 2018).

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Moreover, from 1990 to 2010, the proportion of young Scots pine stands have increased, due to the intensification of harvesting (58- 62% of total annual increment harvested – Levers et al. 2014) and of natural disturbances related to climate change (Seidl et al. 2014). Therefore, understanding the dynamics of belowground biomass and the C sink capability of Scots pine young trees and stands is crucial (Pajtik et al. 2008).

The aim of this study was to estimate root biomass and to develop models for the assessment of belowground biomass of young Scots pine stands growing in oligotrophic conditions in Latvia.

Material and methods

Study sites and sampling

Latvia is situated in the hemiboreal forest zone, with mixed broad leaf-coniferous forests (Ahti et al. 1968). In the study area, the mean annual temperature was +6.4 °C, ranging from -5.3 °C in January to +17.3 °C in July, with the mean annual precipitation of 640 mm (LEGMC 2016). Scots pine covers 29% of the total forest area in Latvia, and approximately half of the stands are located on dry mineral soils (Baumanis et al. 2014). Turf podsoled soils cover more than half of the country (IUCN 1993).

The study material was collected from eight stands during the vegetation period (June to August 2015). The age of the sampled trees ranged from eight to 40 years. Seven of the studied stands had been regenerated using 2-year-old, bare-rooted or containerized seedlings; the soil had been prepared by disk trenching. One of the youngest stands was left to regenerate naturally, without soil preparation. The stands were located on dry, nutrient-poor sandy and silty automorphic soils, and corresponded to *Cladinoso-callunosa*, *Vacciniosa* and *Myrtillosa* forest types, according to the classification by Bušs (1976), which represent the typical conditions of Scots pine forests in Latvia.

In each stand, one circular sampling plot was established (eight sampling plots in total). The plot size varied according to the stand's age: 100 m² (diameter = 11.28 m) in stands younger than 15 years, and 500 m² (diameter = 25.24 m) in the others. In each plot, the diameter at breast height (DBH, ±

0.1 cm) of all trees and the height (H, ± 0.1 m) of 10 sample trees were measured (Tab. 1). To determine the forest type, soil samples were collected from all sampling plots (Tab. 1).

In total, 39 sample trees (2-6 trees per plot), according to the distribution of DBH classes in the stands, were selected randomly for destructive sampling of their root biomass. Trees with visible signs of disease, stem defects (e.g., broken top, double stems), or leaders were avoided. To assess total tree biomass, the fresh weight of aboveground components was determined (± 0.02 kg). Stumps with root components were carefully dug out by hand, separated from soil particles, and washed. The fresh weight of small roots (diameter 2-20 mm), coarse roots (diameter > 20 mm), and the stump (Finér et al. 2011) was measured (± 0.02 kg). Fine roots (diameter < 2 mm) were not collected, as they are associated with the soil microflora, and thus their accurate weight is difficult to assess (Aalde et al. 2006). The stump components included both belowground and aboveground (5-8 cm above the root collar) parts. For the smallest trees (DBH < 5.6 cm), representing all of the 8-year-old sample trees and the six smallest of the 12- to 14-year-old sample trees, only small roots were found. Samples of fresh weight from the tree components (with bark) were collected, dried at 105 °C, and weighed separately for calculating the dry biomass, in accordance with Uri et al. (2002).

Data analysis

Pearson's correlation analysis was used to determine the relationships between the measured variables. To ensure a wide application to the established models of belowground biomass, they were not developed for specific forest site types. Models for stumps, small, and coarse roots, as well as total belowground biomass, were developed for individual trees, based on the aboveground variables: DBH, H, and approximations of stem basal area ($S = DBH^2$) and stemwood volume ($V = DBH^2 \cdot H$).

The regression model (eqn. 1) was:

$$y_i = a + b(x_i) \quad (1)$$

where y_i is the belowground biomass component (kg) of the i -th tree, x_i represents

the independent variables (predictor) for the tree, and a and b are the parameters to be estimated. Additionally, models based on DBH and H as predictors were evaluated (eqn. 2):

$$y_i = a + b(DBH) + c(H) \quad (2)$$

where a , b and c are the parameters to be estimated.

To select the best fitting model for the estimation of belowground biomass components, R² value, F-value, relative error (RE), root-mean square deviation (RMSE), and the Akaike's information criterion (AIC) were used. Modelled data residuals were graphically checked for normality, linearity, homoscedasticity, independency and outlier identification. A logarithmic transformation of data was tested, but preliminary results showed a worst fit to the empirical data; hence, simple linear models were applied. Differences between model predictions and the observed biomass were assessed using t-tests ($\alpha = 0.05$).

To assess the accuracy of the developed models, their predictions were compared to predictions from the models of Repola (2009) for Scots pine stumps and roots (diameter > 10 mm), which have been previously applied in the Baltic Sea region. Coarse root and small root biomass were summed to obtain total root biomass for comparison. The accuracy of the model recently developed for Scots pine belowground biomass in Latvia (Liepins et al. 2018) was also tested, with an emphasis on young stands. The comparisons were made by t-test for paired observations. All statistical analyses were made using the software R version 3.3.1 (R Core Team 2016).

Results

The DBH and H of the sampled trees ($n = 39$) ranged from 1.2 to 18.6 cm, and from 2.2 to 17.5 m, respectively. The mean total belowground biomass (± 95% confidence interval, CI) of young Scots pine was 11.32 ± 5.34 kg, comprising 12-58% of the total tree biomass. The mean ratio (± standard deviation) of the belowground and total tree biomass decreased with tree age; for 8-, 14-, 24- and 40-year-old Scots pine, it was 0.33 ± 0.07, 0.21 ± 0.06, 0.16 ± 0.03 and 0.17 ± 0.01, respectively. Since not all of the trees had coarse roots, the stump ap-

Tab. 1 - Characteristics of sampled Scots pine stands. (H): tree height; (DBH): mean diameter at breast height of sampled trees.

Stand age	Stand location		No. of sampled trees	H (m)	DBH (cm)	Basal area (m ² ha ⁻¹)	Stand density (tree ha ⁻¹)	Forest type
	Lat. N	Long. E						
8	56° 50.54'	24° 38.33'	12	2.6	2.0	2.1	6200	<i>Myrtillosa</i>
	56° 50.60'	24° 38.34'						
12	56° 34.58'	25° 01.21'	2	4.0	6.6	7.3	2145	<i>Cladinoso-callunosa</i>
13	56° 24.58'	25° 11.21'	5	4.6	5.2	4.8	2215	<i>Cladinoso-callunosa</i>
14	56° 51.34'	24° 35.01'	6	4.8	5.3	7.2	3200	<i>Myrtillosa</i>
24	56° 41.00'	24° 27.43'	10	10.0	11.0	13.2	1385	<i>Vacciniosa</i>
40	56° 43.00'	24° 34.62'	4	17.5	19.5	17.1	575	<i>Cladinoso-callunosa</i>
	56° 43.00'	24° 34.12'						

peared to be the largest belowground component, followed by small roots, then coarse roots (Tab. 2). The estimated total belowground biomass of individual trees was highly variable, ranging from 0.7 to 67.4 kg. The mean biomass ± CI of the coarse roots, small roots, and stumps was 7.99 ± 4.29, 2.08 ± 0.65 and 4.18 ± 1.91 kg, respectively.

Significant correlations ($0.61 < r < 0.99$) between the root biomass components and the tree variables were observed (Tab. 3). The belowground biomass components had a stronger correlation with DBH than with H, as the mean r was 0.91 and 0.76, respectively (Tab. 3). Trees with a larger DBH ($R^2 = 0.78$) and H ($R^2 = 0.68$) had greater total belowground biomass, indicating an age-dependent increase (Tab. 3); however, the age effect was not included in the calculations, as it correlated with both DBH and H ($r = 0.69$ and 0.93 , respectively; Tab. 3). Total belowground biomass was highly correlated ($r = 0.99$) with coarse root and stump biomass.

The allometric belowground biomass models (eqn. 1) based on stemwood volume (V) and stem basal area (S) gave the most precise estimates ($R^2 = 0.80$ - 0.98) of root biomass components (Tab. 4), particularly for total belowground ($R^2 = 0.98$) and coarse root ($R^2 = 0.98$) biomass. The models including V as predictor of total, coarse root, and stump biomass estimation demonstrated the highest precision ($R^2 > 0.92$), but the best model for small root biomass prediction ($R^2 = 0.86$) included S as predictor (Tab. 4). Averaged across the sites, the modelled values gave a RE of only 3.6% in the weighed total belowground biomass. Both parameters of the biomass models were significant ($p < 0.05$), except for the intercept for the coarse roots model (Tab. 4). Graphical analysis showed that models based on S and V best performed in the estimation of root biomass components; however, the REs for the total belowground and coarse root biomass were 26% and 43%, respectively, indicating different predictive performances (Tab. 4). The variance explained by the models based on both H and DBH as independent variables was lower ($R^2 = 0.54$ - 0.82).

The models proposed by Repola (2009) and Liepins et al. (2018) significantly ($p < 0.001$) underestimated the actual belowground biomass of young Scots pine in oligotrophic stands, and their predictions were lower compared to our models (Fig. 1). Accordingly, the RE for the predictions of total belowground biomass was 76% using the model proposed by Repola (2009) and 68% using the model proposed by Liepins et al. (2018). Our model of total belowground biomass for young Scots pine in Latvia gave a substantially higher proportion of variance explained (RE = 26%), thus reducing the RE by 42% compared to both previously published models.

Tab. 2 - Mean ratios of root components biomass (± standard deviation) from the measured tree biomass. (AGB): Aboveground biomass; (BGB): belowground biomass.

Root ratio from tree biomass components	Small roots (2-20 mm)	Coarse roots (>20 mm)	Stump	Total BGB
Ratio of total BGB	0.35 ± 0.17	0.22 ± 0.21	0.43 ± 0.12	-
Ratio of AGB	0.12 ± 0.10	0.05 ± 0.09	0.15 ± 0.11	0.33 ± 0.23
Ratio of total tree biomass	0.09 ± 0.06	0.04 ± 0.04	0.10 ± 0.05	0.23 ± 0.10

Tab. 3 - Pairwise Pearson’s correlation coefficients (below diagonal) and their significance (p-values – above diagonal) among variables of young Scots pine trees. (DBH): diameter at breast height; (BGB): belowground biomass.

Variable	Tree height	DBH	Age	Stump biomass	Coarse root biomass	Small root biomass	Total BGB
Tree height	1	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001
Tree DBH	0.86	1	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001
Stand age	0.93	0.69	1	< 0.001	< 0.001	< 0.001	< 0.001
Stump biomass	0.79	0.91	0.73	1	< 0.001	< 0.001	< 0.001
Coarse root biomass	0.80	0.91	0.68	0.96	1	< 0.001	< 0.001
Small root biomass	0.66	0.89	0.61	0.93	0.90	1	< 0.001
Total belowground biomass	0.80	0.92	0.74	0.99	0.99	0.93	1

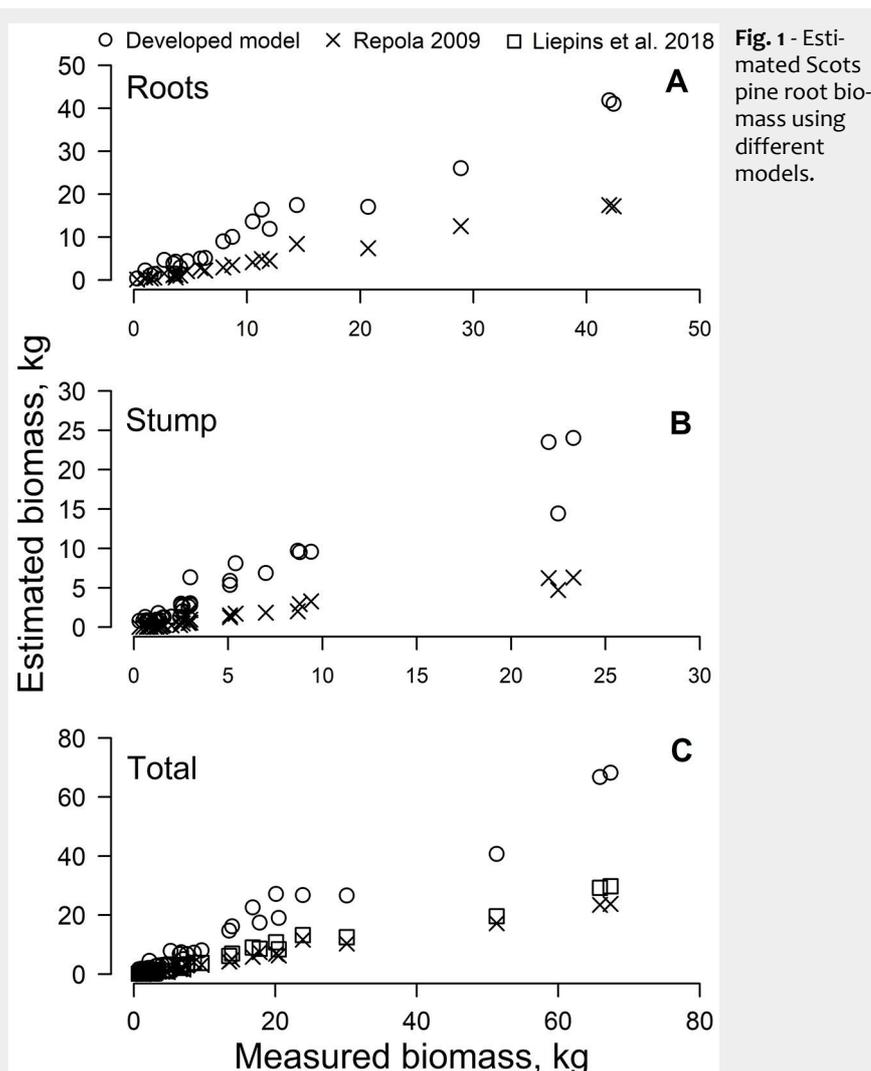


Fig. 1 - Estimated Scots pine root biomass using different models.

Tab. 4 - Parameter estimates and statistics of the models developed for root biomass prediction in young Scots pine trees in Latvia. (S): stem basal area; (V): stemwood volume. Standard error of parameter estimates (*a*, *b*) are given in brackets. (BGB): Belowground biomass; (RMSE): root-mean square deviation; (df): degrees of freedom; (*): $p < 0.05$; (**): $p < 0.01$; (***) : $p < 0.001$.

Model Statistics		Small roots (2-20 mm)	Coarse roots (>20 mm)	Stump	Total BGB
Model		$S = DBH^2$	$V = DBH^2 \cdot H$	$V = DBH^2 \cdot H$	$V = DBH^2 \cdot H$
Parameters	<i>a</i>	0.648*** (0.156)	-0.582 (0.431)	0.766* (0.291)	1.543** (0.496)
	<i>b</i>	196.490*** (13.317)	57.872*** (1.938)	38.421*** (1.746)	110.155*** (2.905)
R ²		0.858	0.977	0.929	0.975
Adj-R ²		0.854	0.976	0.927	0.974
df		1, 36	1, 21	1, 37	1, 37
F-statistics		217.7	891.7	484.0	1438.0
Overall significance (p)		< 0.001	< 0.001	< 0.001	< 0.001
RMSE		0.729	1.471	1.549	2.576
Relative error (%)		36.9	42.6	28.4	25.9

Discussion

In this study, the mean value of the total belowground biomass observed was similar to the estimates obtained for Scots pine in Central Europe (Xiao & Ceulemans 2004), though comparable studies in the literature are still sparse and the belowground biomass estimates highly variable. Moreover, differences in biomass allocation pattern have been observed among populations of Scots pine, with a general trend of lower root biomass in Northern Europe stands (Oleksyn et al. 1999). Such differences have been explained by the effects of forest type, soil structure, moisture regime, and chemical composition (Dieter & Elsasser 2002), which are considered key factors affecting the formation of root systems. This might also be related to age differences among the studied stands, as well as to the competition between young trees leading to their rapid development (Varik et al. 2013). The root system has proven to adapt to different environmental conditions, so trees growing in nutrient-poor forests (as is the case of our study area) are expected to develop a smaller amount of root biomass (Vanninen et al. 1996, Bhuiyan et al. 2017).

The distribution of belowground biomass components (Tab. 2) observed in this study was highly variable, according to previous reports (Fogel 1983, Pajtik et al. 2008, Petersson et al. 2012); however, the belowground biomass estimates (Tab. 2) were comparable to the results of Helmissaari et al. (2002) and Vanninen et al. (1996) in Finnish Scots pine, likely due to environmental conditions similar to those present in Latvia. Further, the ratio of belowground on total biomass of trees decreased with tree age, due to more rapid development of aboveground biomass over the same time span (Uri et al. 2012). Tree dimensions (in terms of DBH and H) showed a strong correlation with belowground biomass

components (Tab. 3); accordingly, both variables could be successfully used for root biomass estimation in nutrient-poor sites, as previously demonstrated by Xiao & Ceulemans (2004) and Lehtonen et al. (2016). Stemwood volume (V) and stem basal area (S), which were included in our models (Tab. 4), have previously been demonstrated to be the best individual variables for fine root biomass estimation (Lehtonen et al. 2016). Since the best prediction of coarse root biomass was obtained using stemwood volume (Tab. 4), models for stump and total belowground biomass estimations were based on this variable. The high accuracy of V in the prediction of root biomass has previously been shown for Scots pine seedlings (Geudens et al. 2004). The stem basal area was the best variable for small root biomass estimation (Tab. 4), indicating a link between the amount of absorbing roots and the crown size with the stem diameter, as proposed by the pipe-model theory (Shinozaki et al. 1964). Overall, biomass models using V as predictor had lower errors (Tab. 4), hence both DBH and H affect tree size over time (Liepins et al. 2018). The coarse root biomass estimates had the highest errors (RE = 43% – Tab. 4), which could be explained by the smaller sample size compared to the other analyzed components. The belowground biomass models developed in this study showed higher precision than previously published models for Scots pine, which were calibrated for a wider spectrum of stand ages (Repola 2009, Liepins et al. 2018). Herein, the application of stump and root models proposed by Repola (2009) led to underestimate the belowground biomass components (Fig. 1), suggesting a limitation for its wider application (Bronisz et al. 2016). The model developed by Liepins et al. (2018) closely followed the values we obtained using the Repola's model (Fig. 1c), indicating that

stand age should be accounted for when estimating precise belowground biomass. Considering that similar belowground biomass estimates were obtained in Estonia (Varik et al. 2013), along with the similarity of Scots pine forest structure therein, we speculate that our models might be successfully applied to predict belowground biomass of young Scots pine trees over the eastern Baltic region. However, a more comprehensive dataset covering a larger area of comparable conditions (Addo-Danso et al. 2016) would be desirable to this purpose.

Conclusions

The models developed in this study reduced the overestimation of belowground biomass of young Scots pine trees, as compared with previously developed models based on a full rotation cycle in the Baltic Sea region. This leads to a reduction of uncertainty in the estimation of carbon budget of belowground biomass. The developed models also appear to be useful tools for the estimation of belowground biomass supply in young Scots pine stands in relation to the potential for bioenergy production. However, the analysis of a more comprehensive dataset is desirable, in order to account for the effect of the social status of trees, and for the withinand between-stand variation.

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