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Biomass equations for lodgepole pine in northern Sweden

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Abstract

Biomass equations for cultivated lodgepole pine (*Pinus contorta* var. *latifolia*) were developed based on data from destructive biomass sampling of 164 trees collected from 13 sites at latitudes 61.9-66.2 ºN in northern Sweden. Stand age varied between 20-87 years and top height between 8-32 m. Seeded and planted stands with different densities were included. Allometric biomass equations for all above-stump components were constructed, expressing dry weight of stem, bark, living and dead branch wood, foliage and cones, as well as total weight. Equations with 1-3 independent variables were constructed for each component, accounting variances within and between sites. Estimated values for trees of different sizes were compared to corresponding estimates for lodgepole pine in Canada and Scots pine in Sweden and Finland. Residual variation of our equations was lower than that of equations from other sources. Our equations predicted similar average biomass levels as Canadian equations for natural stands. In comparison to Scots pine, at given stem dimensions, lodgepole pine had 50-100 % more foliage biomass and greater dead branch biomass with increasing tree size. The wide amplitude of our data and the flexible form of our equations should make them useful for wider application.

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Keywords: destructive biomass sampling, allometric functions

1. Introduction

The growing market for bioenergy in the Nordic countries has targeted forest biomass as an important feedstock (Ericsson et al. 2004). This, together with expectations relating to a future bioeconomy (Octave and Thomas 2009) and carbon stock reporting under the Kyoto protocol, has increased the need for tools to estimate the biomass carbon (C) stocks and energy assets of forests. The C stock and energy assets are highly correlated with dry weight (DW) and can be estimated with biomass equations. Such equations express the dry weight of different components of the tree as a function of easily measured variables like diameter, height and crown length. Different species differ with respect to wood density (Cannell 1989; Zobel and van Buijtenen 1989) and allocation pattern. i.e. crown structure and stem form (Satoo and Madgwick 1982). Thus, separate functions are needed for each species. Biomass equations for Scots pine (*Pinus sylvestris* L.), Norway spruce (*Picea abies* (L.) H. Karst) and birch (*Betula* spp.) in Sweden and Finland have already been developed (Marklund 1988; Claesson et al. 2001; Peterson and Ståhl 2006; Repola 2008; 2009; Repola and Ulvcrona 2014), but no equations are available for lodgepole pine (*Pinus contorta* Dougl.).

As the inland form of lodgepole pine (*Pinus contorta* var. *latifolia*), introduced to Sweden from western Canada on a large scale after 1970 (Elfving et al. 2001), starts to yield significant amounts of biomass there is an urgent need for locally adapted biomass equations for this species. Biomass equations for lodgepole pine are available (Brown 1978; Gholz et al. 1979; Manning et al. 1984), but these equations are based on naturally regenerated trees from North America, and until now the dominant method of regeneration in Sweden has been planting,

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resulting in trees with different allocation of branches and foliage compared to naturally regenerated ones (Long and Smith 1992; Litton et al. 2003).

In a review of available biomass equations, Ter-Mikaelian and Korzukhin (1997) reported two individual studies with biomass equations for lodgepole pine from the grey literature (Brown 1978; Gholz et al. 1979). Both studies are limited in terms of number of sample trees/stands, tree size and biomass fractions analyzed. In both studies three equations are presented i.e. for stemwood including bark, needles and branches. The study by Brown (1978) is based on only eight sample trees in the diameter range 1-5 cm. The study by Gholz et al. (1979) is limited to 29 sample trees with a diameter range from 3-29 cm. The grey literature also provides a larger study by Manning et al. (1984), where biomass equations for lodgepole pine are presented for stemwood, stem bark, branches (diam. > 0.5 cm), twigs (diam. < 0.5 cm) including foliage, and for all above-stump biomass. The data behind the equations originated from 149 sample trees collected from four ecoregions in the Yukon Territory with a diameter range between 3 and 36 cm. The limited information about site and stand characteristics, including regeneration method and stem density, makes it difficult to judge whether these equations are useful for Swedish conditions where most stands are regenerated by planting.

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Based on a thorough review and published data on biomass equations for a number of North American tree species, including lodgepole pine, Jenkins et al. (2003) developed generalized biomass equations for conifers and broadleaves to be used for e.g. large scale inventory-based C budgets. Their work was further developed by Chojnacky et al. (2014) and included an update of published data. In both studies, pseudodata were generated within the diameter limitations of published equations. The pseudodata were then used to construct generalized total biomass equations over the full diameter range based on a two-parameter logarithmic regression model with diameter at breast height (DBH) as the independent variable (ln(biomass) = β0 + β1 x ln(DBH)). With all the uncertainties included in such an approach, Chojnacky et al. (2014) concluded the need for better data to be collected across the distribution ranges of different tree species and Jenkins et al. (2003) suggested a common protocol for biomass estimate studies and that researchers, in addition to publishing their biomass equations, also published the data from which their equations were developed.

Thus, despite inclusion of unpublished reports, we found few studies relating to lodgepole pine, and those found were mostly based on few and small trees. No new, more comprehensive studies have been found. It appears that there is a world-wide need for biomass equations for lodgepole pine. Here we present such equations for different fractions of lodgepole pine trees based on 164 sample trees sampled in 13 stands in Sweden and we include the data behind the equations as an appended Excel-file. The equations are compared with the equations published by Manning et al. (1984) to indicate whether they could also be useful for estimates within the natural range of lodgepole pine.

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2. Material and methods

2.1 Site and stand descriptions

The sample trees were collected in northern Sweden, from latitude 61.9 ºN in the south to latitude 66.2 ºN in the north (Figure 1, Table 1). Altitude varied between 80 and 440 metres above sea level and stand age between 20 and 87 years. Number of stems ha^{-1} varied between 450 and 6034, basal area between 12 and 51 m^{2} ha^{-1} and top height between 8 and 32 m (Table 1). The distributions of sample trees over height- and diameter classes are given in Table 2.

Some sites hosted long-term yield plots in field experiments but sample trees were only affected by applied treatments in two of them: the spacing trial 1209 at Långsjönäset and the scarification trial 1544 at Degerön. At Långsjönäset the square spacings 1.1, 1.6, 2.0, 2.85 and 4.0 m were represented and sample trees were selected from all spacings. At Degerön the treatments were ordinary patch scarification and deep ploughing on a poor sediment of deep sand and the sampling included both treatments. The sites Toböle 2 and Korseleberget represent the first plantations of lodgepole pine in Sweden established in 1931 (Toböle 2) and 1928 (Korseleberget).

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<Figure 1 here >

<Table 1 here>

<Table 2 here>

2.2 Sampling procedure

In total, 164 trees were sampled from 13 different sites during the years 1999-2012 (Table 1). The same sampling procedure was applied in all but one study (Toböle 1999). First the main procedure used is described and after that the deviations for the Toböle 1999 study.

Sample trees were selected by stratified (by DBH) random sampling among undamaged trees in each plot. Forked trees and trees at stand borders were avoided. Diameter at breast height (DBH, diameter over bark at 1.3 m above ground, cm) was marked and cross-callipered to the nearest mm before felling. The aim of the biomass sampling was to estimate dry weight above ground, and therefore each sample tree was cut down as close to the ground as possible. Measurements of the felled trees included total stem length (L, m) and distance from stem base to the living crown, defined as the lowest living branch separated from other living branches by less than three whorls. Diameter was cross-callipered at the base of the stem, and at each metre up to the top. The living crown was divided into four sections, each of which accounted for 25% of the crown length (Figure 2). One branch ocularly judged to be representative of each section was selected and cut using pruning shears. In addition, a representative dead branch was selected from below the living crown of each sample tree. Stem discs (5 cm thick) were cut with a bow saw (scar width 1.5 mm) or a chain saw (scar width 8 mm used for the larger trees) from the butt end of the stem, at breast height (1.3 m), and at four positions representing 30, 55, 70 and 85% of the total stem length (Figure 2). Scar widths were estimated by comparing the weight of some pieces of wood before slicing with the different saws with the weight of the resulting discs. The saw-dust lost with the chain saw was compensated for but not that from the bow saw. Directly after felling and dividing a tree the sample discs and sample branches were weighed in the field on a laboratory balance (6 kg maximum, ± 0.0005 kg) to obtain the fresh weight. The remaining stem sections and all other branches from each section were weighed on a scale (30 kg maximum, ± 0.002 kg). For the sampling in Toböle and Korseleberget in 2012, a scale with 100 kg maximum was used for the remaining stem sections and branches. All sample branches and disc samples for individual sample trees were put in separate airtight plastic bags and within 8 hours from the time of tree felling, the samples were placed in a freezer (- 20 °C), where they were stored until it was time to determine their dry weight .

<Figure 2 here>

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The sectioning of the stem was used to estimate the stem volume and served as a back-up for checking the stem form and weight. Stem volume over bark (V, dm^3) was estimated as:

(1) $$V= (\pi/4000) (\Sigma(d_i)^2 +0.5 ((2d_0+d_1)/3)^2)$$

where d_i is the diameter (mm) at the upper end of each 1-m stem section and d_0 is the diameter at the lower end of the first section. This corresponds to Huber´s formula with addition of an approximation for the bottom half-meter section.

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For nine of the sites (in total 119 sample trees) the bark was separated from the discs in the laboratory, and both fractions were immediately weighed on a laboratory balance (6 kg maximum, ± 0.0005 kg) to obtain separate fresh weights for the disc (wood) and the bark. Discs and bark, or discs including the bark, were dried in a ventilated oven at 85 °C for 48 hours before measuring their dry weight. The discs where then further dried until their weight didn’t decrease any more. For living branches, foliage was separated from the branches after 24 hours of drying in a ventilated oven (85 °C), whereas the cones were combined with the branches. The different fractions were then further dried for another 24 hours before weighing. Dead branches were treated as one fraction without needles and were dried in a ventilated oven at 85 °C for 48 hours before measuring their dry weight.

Dry weights for biomass components (DW_x, kg dry weight per tree) were estimated from measured data as follows, where all disc and section values include bark:

Stem including bark ($\mathrm{DW}_{\mathrm{stem}}$)

$$\text{(2)}\qquad \mathrm{DW}_{stem} = \Sigma\left(\frac{\left(\frac{DW_{disc\ i}}{FW_{disc\ i}} + \frac{DW_{disc\ i+1}}{FW_{disc\ i+1}}\right)}{2} \times FW_{stem\ section\ i} + DW_{disc\ i}\right)$$

where $DW_{disc\ i}$ is the dry weight of disc *i*, $FW_{disc\ i}$ is the fresh weight of disc *i*, $FW_{stem\ section\ i}$ is the fresh weight of the stem section with *i* in the range 1 to 6 including all stem sections from stump to top. For *i*=6 the index *i*+1 was reduced to 6.

Bark ($\mathrm{DW}_{\mathrm{bark}}$)

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$$\text{(3)}\qquad \mathrm{DW}_{bark} = \Sigma\left(\frac{\left(\frac{DW_{bark\ i}}{FW_{disc\ i}} + \frac{DW_{bark\ i+1}}{FW_{disc\ i+1}}\right)}{2} \times FW_{stem\ section\ i} + DW_{bark\ i}\right)$$

where $DW_{bark\ i}$ is dry weight of the bark of disc *i* . Other acronyms are as defined under equation (2).

Living branches ($\mathrm{DW}_{\mathrm{lbr}}$)

$$\text{(4)}\qquad \mathrm{DW}_{\mathrm{lbr}} = \sum FW_{stratum.j} \times \left(\frac{DW_{sbw.j}}{FW_{sb.j}}\right)$$

where $FW_{stratum\,j}$ is the fresh weight for stratum j including the sample branch, with j in the range 1-4. $DW_{sbw.j}$ is the dry weight of the sample of branch wood including cones and $FW_{sb.j}$ is the fresh weight of the sample branch.

Foliage (DW_{fol})

$$DW_{fol} = \sum FW_{stratum.j} \times \left(\frac{DW_{sbf.j}}{FW_{sb.j}} \right) \quad (5)$$

where $DW_{sbf.j}$ is the dry weight of the foliage of the sample branch j, and other acronyms are as defined under equation (4).

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Dead branches (DW_{dbr})

$$DW_{dbr} = FW_{DB} \times \left(\frac{DW_{dsb}}{FW_{dsb}} \right) \quad (6)$$

where FW_{DB} is the total fresh weight of dead branches, DW_{dsb} is the dry weight of the dead sample branch and FW_{dsb} is the fresh weight of the dead sample branch.

Cones (DW_{cone})

$$DW_{cone} = \sum FW_{stratum.j} \times \left(\frac{DW_{sbc.j}}{FW_{sbj}} \right) \quad (7)$$

where $DW_{sbc.j}$ is the dry weight of cones on the sample branch j and other acronyms are as defined under equation (4).

For the Toböle site sampling in 1999, a slightly different sampling procedure was used (Elfving, 2002). Diameter at breast height was marked and cross-callipered to the nearest mm before felling. Tree height was measured, and stump height was marked at 1 % of tree height before felling. After felling, the length of the stem was measured. All dead branches were directly gathered and weighted and a representative sample of about 1 kg was selected for dry weight determination in the laboratory. All living branches were divided into branch fractions with and without needles. Total fresh weight was determined for both groups, representative samples (about 1 kg) were selected from each group and their fresh and dry weights were determined. Stem discs 5 cm thick were cut at 1.5 m and then every 3 m up the stem. Drying of the samples to determine dry weight followed the same procedure as above. Stem volume was estimated as 3π/4 times the sum of squared disc diameters, and stem biomass as volume times mean wood density according to the basal area weighted mean of the stem discs.

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By convention, stump height is generally defined as 1 % of tree height. In this study only the length from stump to tree top on the felled tree (L, m) was measured (except at Toböle 1999 when tree height was measured for the standing tree). To ensure conformity with other studies, measured data was adjusted as follows. Tree height above ground (H, m) was estimated as H= L/0.99.

2.3 Statistics

Allometric biomass equations of the form $\ln(Y)=b_0 + b_1\cdot\ln(x_1) + b_2\cdot\ln(x_2)$ … were estimated for dry weight (kg) of the total tree above-stump (DW_{tot}) and for the components stem with bark (DW_{stem}), living branches (DW_{lbr}), dead branches (DW_{dbr}) and foliage (DW_{fol}) using the procedure MIXED in the SAS statistical package. Two-three levels of equations were estimated for each component including different numbers of explanatory variables: (1) only based on DBH, (2) based on DBH and H, (3) based on DBH, H and crown length (crl). Appropriate forms of the partial relationships were found by residual studies. The within and between site variation was separated with the MIXED procedure, specifying site as a random class variable according to the model:

$$\ln Y_{ij}=b\times X_{ij} + u_j + e_{ij} \quad (8)$$

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where Y_{ij} is measured biomass of actual component for tree i at site j, b is a vector of coefficients, X_{ij} is a vector of explanatory variables, u_j is the random effect for site j and e_{ij} is the random effect for tree i at site j. It is assumed that u_i and e_{ij} are un-correlated and have normal distributions with mean=0. The error terms are model parameters which variances are to be estimated.

For the partial relationship with DBH, the transformations ln(DBH) and DBH/(DBH+x) were tested, with a search process to find the most appropriate value of x for each biomass component. The latter formulation was used by Marklund (1988) and Repola (2008, 2009) for Scots pine, Norway spruce and birch ssp. biomass in Sweden and Finland. The differences were marginal for our data and the first form was chosen since it performed well for all components. Tree height was an important variable for estimating biomass of all components except that of dead branches while crown length was important for estimating branch- and foliage biomass. To get an appropriate partial relationship of stem biomass to height, both height (lnH) and height above breast height (ln(H-1.3)) were included for this component as well as in the equation for total biomass. The most commonly applied volume equations for pine and spruce in Sweden (Brandel 1990) also include this partial relationship of stem volume to height. Since stem biomass and stem volume are closely related it seems as if this form of the relation between stem size and height is quite general.

The variable H/(DBH) describes stem form (slenderness) and was more significant than ln(H) for estimating the foliage biomass. Since logarithmic transformation causes bias in the absolute scale, the additive coefficients in the equations were adjusted by including the following correction (adj), according to Snowdon (1991):

$$(9) \qquad adj=\ln(\Sigma DW_{obs})-\ln(\Sigma \exp(\ln(DW_{Eq})))$$

where ΣDW_{obs} is the sum of observed biomass of the actual component in absolute terms and $\ln(\Sigma DW_{Eq})$ is the sum of the unadjusted values given by the equation. The intercepts in Table 3 have been corrected in this way.

Data on the fraction of bark biomass were only available for 119 trees from nine sites. Bark biomass (DW_{bark}) was expressed as bark proportion (Bp) of the stem biomass ($Bp=DW_{bark}/DW_{stem}$) and was studied as a function of DBH and H. The best correlation was found with the transformed variable 1/(H+3). The variation in bark proportion within the stem was also studied based on stem disc data. The dependent variable was then the bark proportion of

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the disc biomass including bark (Bp_{disc}). The best model included a second-degree polynomial of disc relative height position (Hrel, $Hrel^2$) and the transformed variable 1/(H+3). The variable Hrel (h/H, where h is height above stump) is defined in the interval 0-1 where 0 is stump height and 1 is tree top.

Since lodgepole pine often retains its cones for decades (Elfving et al. 2001), the cone biomass can form a substantial part of the branch biomass. This amount was examined based on data from 64 trees from five sites where the fresh and dry weights of cones were measured separately from the branch samples. Since the appearance of cones was stochastic (several examined trees lacked cones on the sample branches) a two-step model for estimation of cone biomass (DW_{cone}) was formulated. In step one the probability that there are no cones (plc) was estimated with a logistic regression:

$$(\ln(1/plc-1)=b_0+b_1\cdot(H/(DBH+1)) \quad (10)$$

where plc is probability that there are no cones on the sampled branches from a tree and b_0 and b_1 are coefficients to be estimated.

In step two, the biomass of cones on trees with cones (DW_{c1}) was estimated with ordinary least squares regression (OLS). Dry weight of cone biomass is estimated by combining the logistic and OLS equations as:

$$DW_{cone} = DW_{c1} \times (1-plc) \quad (11)$$

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The estimated stem volumes according to the sectioning were used to identify outliers in the data. One stem was deleted since the stem weight and the sectioned volume did not correspond. Two trees were outliers from the biomass equations and it was found that their DBH-values deviated more than three times the expected measurement error from the stem profile according to the sectioning. The original DBH-value was then replaced with the value estimated from the stem profile curve.

3. Results

Equations for estimation of total tree biomass and for the tree components: stem with bark, living branches with cones, foliage and dead branches are presented in Table 3. Equations for separate estimation of bark proportion and the biomass of cones are presented in Table 4 and residuals in relation to observed data are shown in Figures 3-4. All independent variables included in the equations were highly significant (p<0.01). Inspection of the residuals confirmed that they fulfilled the assumptions done in the model formulation.

<Tables 3-4 and figures 3-4> here

4. Discussion

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The data for this study came from cultivated stands older than 20 years with top heights above 7 m. The equations are therefore not valid for younger stands. Initial growing conditions have a large impact on tree shape (Lindgren et al. 2007). The sample trees represent a wide variety of growing conditions. The provenances used were all from the interior of Canada between latitudes 54 and 61ºN and represent the provenances recommended for cultivation in northern Sweden.

Level 1-equations with only diameter as the independent variable had large residual variations, with between-site variation as the dominant component. They are not recommended for practical use but are included to demonstrate the increased efficiency of including more independent variables. Inclusion of top height according to Table 3 in the model reduced the residual variance substantially (calculation not shown). Stand height can be efficiently estimated by airborne laser scanning (Nilsson et al. 2015) and should always be included in future large-scale biomass estimations.

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Our sampling was not focussed on a specific population of lodgepole pine. Instead we tried to include stands with as many different conditions we could find regarding stands density, developmental stages, site conditions etc. This means that we could expect a larger between-stand residual variation than what is found in data from ordinary population sampling. For example, at Örnåsen all biomass components except dead branches had lower biomass than expected ($p<0.01$) and at Degerön they were all higher than expected ($p<0.001$). Also at Korseleberget all components had more biomass than expected but the deviation had lower significance ($p=0.051$).

The sampling was spread over the snow-free season, from May to October (Tab. 1), which influence the foliage biomass (DW_{fol}). If there are four fully developed age classes of needles at the peak of DW_{fol} in late July and three classes left when the oldest class has been shed in late autumn, the summer DW_{fol} would be about 30 % larger than the winter DW_{fol}. Our equations probably give average values between those extremes. It should be noted that for single trees the sum of predicted biomasses for different components generally deviates from the value predicted by the equation for total biomass. The latter value is the best prediction of total biomass, and the component sum can be brought into agreement with this value by proportional adjustment. In our data the adjustment factor is in average 1.00 with the standard deviation 0.03. This adjustment method is of course approximate. Different methods for additive modelling have been proposed, restricting results from the partial relations to add up to the total (Parresol 2001, Poudel and Temesgen 2016, Zhao et al 2016). Our aim was however to construct flexible partial equations that can be used separately for different purposes. We did not try direct additive modelling but our data are enclosed and can form a basis for further development of the modelling methods.

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Results from this study were compared with predicted biomass for lodgepole pine in Canada according to Manning et al (1984) and for Scots pine in Sweden and Finland according to Marklund (1988) and Repola (2009), Table 5. The Canadian study was based on data from 149 lodgepole pine trees in the Yukon Territory. The Marklund study was based on data from 493 Scots pine trees forming a representative sample from the whole of Sweden, while the Repola study was based on data from 908 Scots pine trees representing both research plots and ordinary forests in Finland. The comparisons were conducted for small, medium and large trees with central values of diameter and height according to Table 2 as independent variables.

<Table 5> here

The residual variation was smaller for the equations developed in this study than for the other equations in the comparison (Table 5). One reason for this is probably smaller measurement errors. The weighing of the whole tree used in this study gives high precision for the biomass estimates. Another reason for smaller errors may be better specified partial relations.

In the Canadian study, residuals were given in absolute form and could not be translated to a form comparable to the other studies. Instead the residuals presented here are those obtained when we applied the Canadian model to our data. Living crown was split into larger branches and twigs with foliage. Thus, comparable biomass components were stem with bark and living tree crown. The Canadian values for dead branches refer to air-dry and not oven-dry weight.

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For lodgepole pine, stem biomass was about 10 % larger according to the Canadian model than according to our equation. This may be due to a higher wood density in the naturally regenerated and dense stands in the Yukon, with slow-growing trees.

The Yukon values for living crown biomass (in average 71.7 kg according to table 5) are almost equal to those in our study (in average 72.2 kg). For dead branches biomass the Yukon values are 14 % higher than our values. The higher Yukon values for dead branches depends probably on moisture remaining in the air-dried branches. The fresh weight of dead branches was, on average, 33 % higher than their dry weight in our data. This relationship varied between sites in the interval 15-55 %, probably mostly related to the weather conditions before and during sampling. In conclusion, the Canadian biomass equations by Manning et al (1984) seem to give comparable biomass values as our equations.

The Canadian study included separate equations for stem biomass under bark and stem bark. According to those equations, estimated bark proportion for the trees in Table 5 was about 20 % higher than that estimated with the equation for bark proportion of stem dry weight in our study. Cone biomass was also included in the branch biomass in the Canadian study and could not be directly compared. At the five sites in our data where cones were separated they accounted for, on average, 14 % of the branch biomass. Average dry weight per cone was 7.5 g.

For Scots pine, Marklund (1988) and Repola (2009) predict similar values for biomass of different components. However, for large trees Repola (2009) predicts smaller dry weight for the stem. The larger stem weight for Scots pine according to Marklund (1988) is almost the same as for lodgepole pine according to this study. This looks like a coincidence, since both bark thickness at breast height and probably also average wood density are larger for Scots pine than for lodgepole pine. The higher wood density is because of the slower growth rate of Scots pine on comparable sites, cf. Persson 1993. The most striking difference in biomass between lodgepole pine and Scots pine concerns foliage and dead branches. Lodgepole pine is predicted to have 50-100 % higher foliage biomass than Scots pine, while the proportion of dead branches of total crown biomass is almost the same for small trees (20 %), but increases to 30 % in large lodgepole pine and decreases to 15 % in large Scots pine. Those differences are certainly species-specific.

The stump-root system was not included in this study. According to Marklund (1988) this component constituted 20-25 % of the total tree biomass for both Scots pine and Norway spruce of common tree sizes (DBH=6-25 cm, H=5-20 m). In this case, the stump-root system included the roots that were still attached to the stump when the tree had been pulled down. The similarity

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between pine and spruce in this aspect may indicate that similar values can be expected for lodgepole pine.

Peterson and Ståhl (2006) examined the biomass of the smaller roots and found that the Marklund (1988) values should be increased by 6 % to include all roots down to 5 mm and by 11 % to include all roots down to 2 mm. New functions based on an extended data-set were also presented. It was found that the biomass of the stump-root systems were larger on moist than on mesic and dry sites.

In conclusion the biomass equations presented for lodgepole pine had smaller residuals than other comparable biomass equations for lodgepole pine and Scots pine, and estimated biomass in different tree components deviated from these other equations as expected. The wide amplitude of our data and the flexible form of our equations should make them useful for a wide range of applications, both for detailed analyses at the single tree level and for large-scale estimates at the stand- and forest levels.

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Table 1. Stand data, sample year and number of sample trees per site

Site	*Alt. (m) (a.s.l)*	*Age years*	*Top height (m)*	*Number of stems ha^{-1}*	*Basal area m^2 ha^{-1}*	*Sampling year-month*	*Number of sample trees*	*Experim. number/ reference*
Örnåsen	370	26	14-16	1630-1790	27-31	2010-10	19	1156
Långträsk	260	31	13-14	1830-2080	26-28	2010-10	13	1155
Långsjönäset	360	40	15-18	500-6034	17-51	2008-05	29	1209
Kälvjärv	150	28	8-9	1053-1614	10-14	2005-10	20	Ref 1
Snägden	160	25	13	1725	24	2006-07	11	Ref 2
Rödmyrdalen	150	29	15	2320	36	2006-07	10	Ref 2
Toböle 1	80	48	19	860	28	1999-05	8	Ref 3
Toböle 1	80	61	26	610	30	2012-09	4	1113
Toböle 2	80	84	32	450	45	2012-09	4	1962
Korseleberget	350	87	28	540	34	2012-10	8	1959
Tönningstenen	440	29	9	3663	12	2011-09	2	Ref 4
Framsängsån	230	29	13	2338	29	2011-09	2	Ref 4
Bjärkliden	325	20	8	5000	21	2012-09	18	Ref 5
Degerön	150	27	10-12	2500	16-22	2012-09	16	Ref 6

Note. Experiment numbers refer to the Swedish database Silva Boreal (2014) for forest field experiments. References: ref 1: Kero 2007; ref 2: Gardmo 2007; ref 3: Elfving 2002; ref 4: Backlund and Bergsten 2012; ref 5: Ulvcrona et al. 2013; ref 6: Egnell et al. 2015.

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Table 2. Distribution of biomass sample trees in the different height- and diameter classes. Number of sample trees in each class.

H-class						*DBH class, cm*										
m	4-6	-8	-10	-12	-14	-16	-18	-20	-22	-24	-26	-28	-30	-32	-34	-36	Total
4-6	1	2															3
-8		10	8	6	1												25
-10	1	4	3	12	4	1											25
-12		3	5	6	4	5	1										24
-14		2	2	2	4	9	4	4									27
-16			1	4	7	2	7	4	1	2							28
-18					2	3	1	3		1							10
-20					1	1		1	2								5
-22								1	2								3
-24									3			2			1		6
-26											1		2	1			4
-28															1		1
-30											1			1		1	3
Total	2	21	19	30	23	22	13	13	8	3	2	2	2	2	2	1	164

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Table 3. Biomass equations for lodgepole pine, giving the dry weight (DW, kg) of different components as a function of DBH over bark (DBH, cm), total tree height (H, m) and length of living crown (crl, m). The terms s^2sites and s^2trees denotes the residual variances between and within sites, and Sres-tot $= \sqrt{(s^2\text{sites}+s^2\text{trees})}$ is the total residual error of the equation. Standard errors of the coefficients are given in parenthesis below the coefficients

	Coefficients for independent variables								
Dependent variable	Intercept^1	ln(DBH)	ln(H)	ln(H-1.3)	H/ DBH	ln(crl)	s^2 sites	s^2 trees	Sres-tot
All above stump: ln(DW_{tot})	-2.177 (0.089)	2.371 (0.028)					0.0320	0.0097	0.204
	-3.958 (0.336)	2.182 (0.033)	2.852 (0.840)	-2.062 (0.744)			0.0025	0.0075	0.100
Stem with bark: ln(DW_{stem})	-1.834 (0.138)	2.121 (0.035)					0.1379	0.0154	0.392
	-5.235 (0.281)	1.729 (0.026)	4.832 (0.690)	-3.265 (0.610)			0.0024	0.0045	0.083
Living branches: ln(DW_{lbr})	-7.665 (0.293)	3.601 (0.093)					0.3143	0.1108	0.652
	-4.619 (0.216)	4.269 (0.113)	-1.858 (0.141)				0.0086	0.0939	0.320
	-4.655 (0.208)	3.657 (0.133)	-1.967 (0.132)			0.940 (0.136)	0.0103	0.0718	0.287
Foliage ln(DW_{fol})	-5.642 (0.272)	2.717 (0.085)					0.3951	0.0912	0.697
	-1.708 (0.441)	1.759 (0.114)			-1.432 (0.168)		0.0368	0.0839	0.348
	-1.577 (0.404)	1.101 (0.149)			-1.547 (0.154)	0.834 (0.134)	0.0322	0.0677	0.316
Dead branches: ln(DW_{dbr})	-6.235 (0.349)	2.797 (0.120)					0.2321	0.1963	0.655
	--6.052	3.609				-1.138	0.163	0.171	0.577

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	(0.320)	(0.188)	(0.213)

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[1] Corrected for logarithmic bias

Table 4. Equations for bark proportion of stem biomass and for cone biomass. H is the tree height (m), H_{rel} is relative height (stump=0, top=1), DW_{c1} is dry weight of cones in branch samples with cones, plc is the probability of cones being absent from the branch sample

Dependent variable	*Coefficients*								
	Intercept	1/(H+3)	Hrel	$(Hrel)^2$	ln (H)	H/ (DBH+1)	Adj. R^2	s_{res}	n
Bark prop. of DW_{stem}	0.0524	0.5073					0.437	0.0109	119
Bark prp. of DW_{disc}	0.0418	0.7275	-0.1222	0.2350			0.722	0.0192	714
$\ln(DW_{c1})$	-0.1128				2.2768	-7.1103	0.610	1.087	54
ln(1/plc-1)	14.63					-12.82			64

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Table 5. Estimated biomass (kg per tree) of different tree components of three tree sizes according to equations from this study and from other studies. Figures in italics indicate residual standard deviation of the different equations

Tree variables		*Biomass component*					*Biomass component*				
DBH (cm)	H (m)	DW$_{stem}$	DW$_{lbr}$	DW$_{fol}$	DW$_{dbr}$	DW$_{tot}$	DW$_{stem}$	DW$_{lbr}$	DW$_{fol}$	DW$_{dbr}$	DW$_{tot}$
		lodgepole pine-this study					Scots pine-Marklund 1988				
S$_{res}$		*0.083*	*0.320*	*0.348*	*0.655*	*0.100*	*0.196*	*0.456*	*0.527*	*0.945*	-
7	9	8.0	0.7	0.9	0.5	10.4	7.8	1.4	0.6	0.4	10.2
15	15	53.8	6.8	5.0	3.8	72.0	54.6	9.6	3.2	2.0	69.4
30	25	351.5	50.4	22.5	26.6	452.5	340.7	38.8	10.3	6.4	396.2
		lodgepole pine-Manning et al 1984					Scots pine-Repola 2009				
S$_{res}$		*(0.10)*[1]	*(0.70)*	*(0.60)*	*(0.59)*	*(0.14)*[1]	*0.110*	*0.361*	*0.476*	*0.784*	*0.138*
7	9	8.5	1.0	1.7	0.3	11.5	8.2	0.9	0.6	0.4	10.2
15	15	59.0	6.0	5.9	4.6	75.6	55.4	6.9	3.3	2.2	69.4
30	25	388.2	38.7	33.0	33.1	493.1	309.7	37.8	11.4	10.2	374.3

[1] Values in parentheses are residuals when the Manning model is used with our data, that is use of D^2H as the only independent variable for all components with OLS on our data.

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Figure legends

Figure 1. Map showing location of all sites for biomass sampling. Latitude and longitude are given in degrees, minutes and seconds (WGS84).

Figure 2. The sampling procedure. In the field the raw weight was determined for 6 discs, 6 stem sections (between discs), 4 living sample branches (one per strata), 4 living branch strata, 1 dead sample branch, 1 dead-branch bunch. Discs and sample branches were brought to the lab for drying and dry weight determination.

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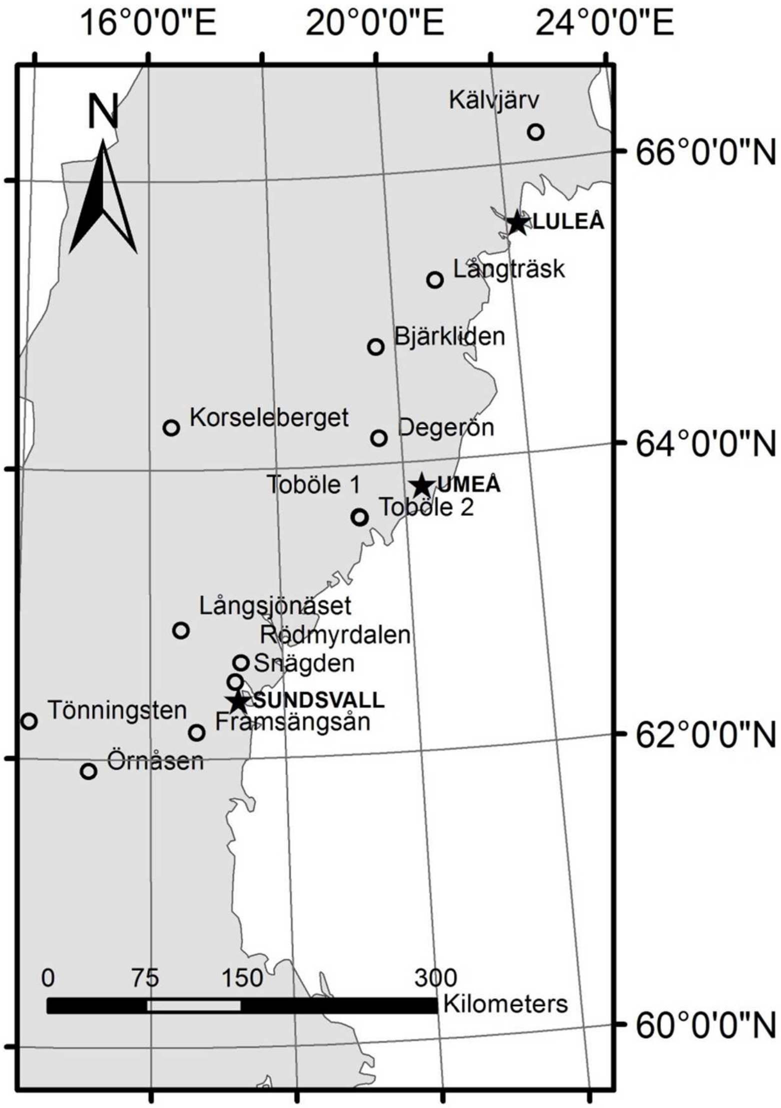
Figure 3. Observed and estimated bark proportion of stem biomass according to equations in Table 4: in total for stems of different heights (upper diagram) and in stem discs at different levels in the stem (lower diagram).

Figure 4. Observed and estimated cone biomass per tree according to the equations in Table 4. Points mark mean observed values in different classes and figures are number of observations in that class. The dashed line is the reference (regression).



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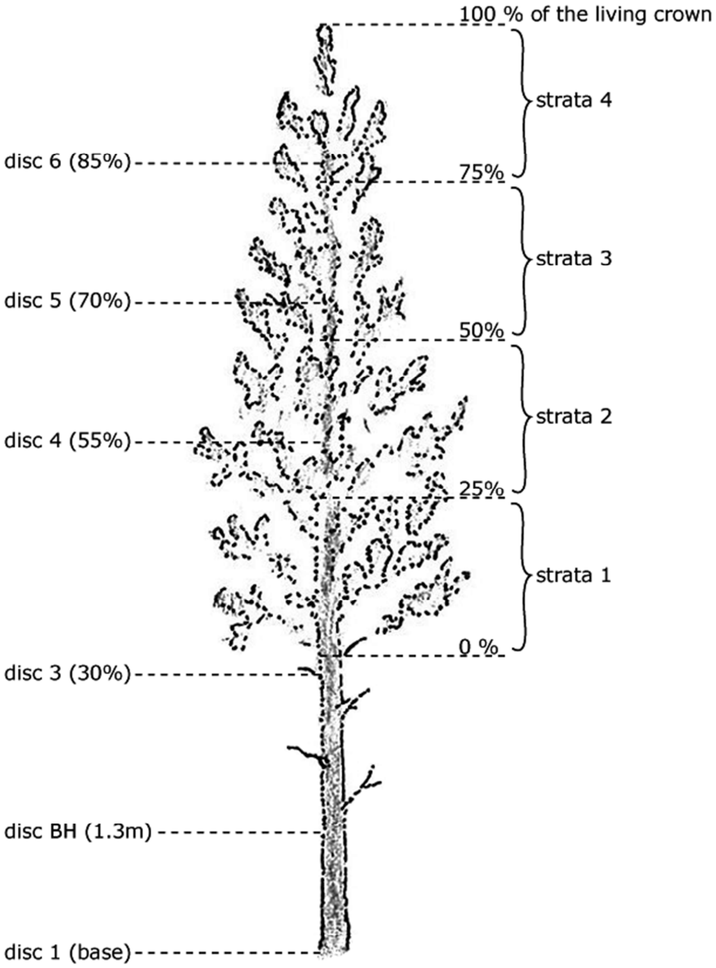

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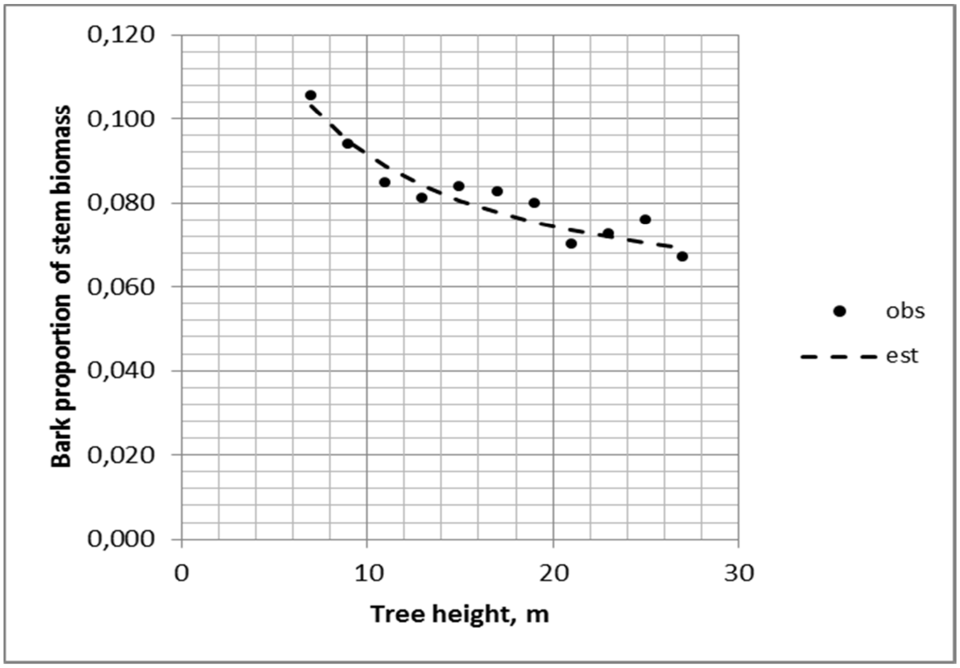

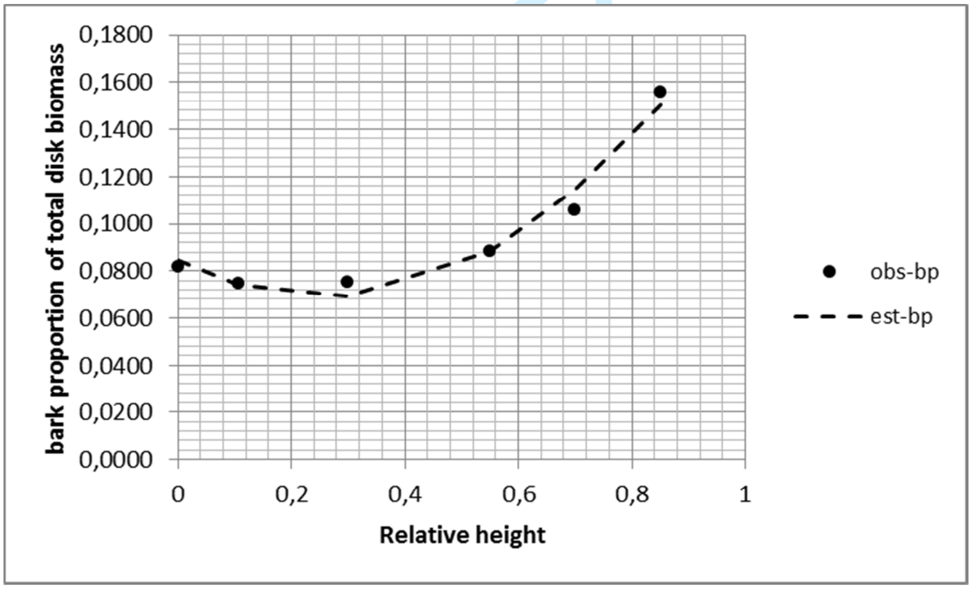

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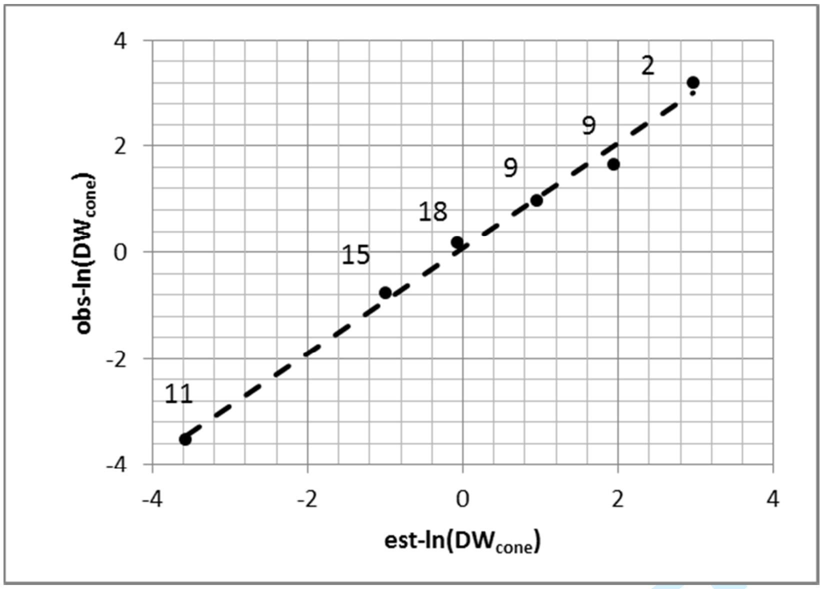

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Kälvjärv	150	28	8-9	1053-1614	10-14	2005-10	20	Ref 1
Snägden	160	25	13	1725	24	2006-07	11	Ref 2
Rödmyrdalen	150	29	15	2320	36	2006-07	10	Ref 2
Toböle 1	80	48	19	860	28	1999-05	8	Ref 3
Toböle 1	80	61	26	610	30	2012-09	4	1113
Toböle 2	80	84	32	450	45	2012-09	4	1962
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Framsängsån	230	29	13	2338	29	2011-09	2	Ref 4
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-8		10	8	6	1												25
-10	1	4	3	12	4	1											25
-12		3	5	6	4	5	1										24
-14		2	2	2	4	9	4	4									27
-16			1	4	7	2	7	4	1	2							28
-18					2	3	1	3		1							10
-20					1	1		1	2								5
-22								1	2								3
-24									3			2			1		6
-26											1		2	1			4
-28															1		1
-30											1			1		1	3
Total	2	21	19	30	23	22	13	13	8	3	2	2	2	2	2	1	164

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	Coefficients for independent variables								
Dependent variable	Intercept[1]	ln(DBH)	ln(H)	ln(H-1.3)	H/ DBH	ln(crl)	s^2 sites	s^2 trees	Sres-tot
All above stump:	-2.177	2.371					0.0320	0.0097	0.204
$\ln(DW_{tot})$	(0.089)	(0.028)							
	-3.958	2.182	2.852	-2.062			0.0025	0.0075	0.100
	(0.336)	(0.033)	(0.840)	(0.744)					
Stem with bark:	-1.834	2.121					0.1379	0.0154	0.392
$\ln(DW_{stem})$	(0.138)	(0.035)							
	-5.235	1.729	4.832	-3.265			0.0024	0.0045	0.083
	(0.281)	(0.026)	(0.690)	(0.610)					
Living branches:	-7.665	3.601					0.3143	0.1108	0.652
$\ln(DW_{lbr})$	(0.293)	(0.093)							
	-4.619	4.269	-1.858				0.0086	0.0939	0.320
	(0.216)	(0.113)	(0.141)						
	-4.655	3.657	-1.967			0.940	0.0103	0.0718	0.287
	(0.208)	(0.133)	(0.132)			(0.136)			
Foliage	-5.642	2.717					0.3951	0.0912	0.697
$\ln(DW_{fol})$	(0.272)	(0.085)							
	-1.708	1.759			-1.432		0.0368	0.0839	0.348
	(0.441)	(0.114)			(0.168)				
	-1.577	1.101			-1.547	0.834	0.0322	0.0677	0.316
	(0.404)	(0.149)			(0.154)	(0.134)			
Dead branches:	-6.235	2.797					0.2321	0.1963	0.655
$\ln(DW_{dbr})$	(0.349)	(0.120)							
	--6.052	3.609				-1.138	0.163	0.171	0.577
	(0.320)	(0.188)				(0.213)			

[1] Corrected for logarithmic bias

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	Intercept	1/(H+3)	Hrel	$(Hrel)^2$	ln (H)	H/ (DBH+1)	Adj. R^2	s_{res}	n
Bark prop. of DW_{stem}	0.0524	0.5073					0.437	0.0109	119
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		lodgepole pine-this study					Scots pine-Marklund 1988				
S_{res}		*0.083*	*0.316*	*0.348*	*0.629*	*0.100*	*0.196*	*0.456*	*0.527*	*0.945*	-
7	9	8.0	0.7	0.9	0.5	10.4	7.8	1.4	0.6	0.4	10.2
15	15	53.8	6.8	5.0	3.8	72.0	54.6	9.6	3.2	2.0	69.4
30	25	351.5	50.4	22.5	26.6	452.5	340.7	38.8	10.3	6.4	396.2
		lodgepole pine-Manning et al 1984					Scots pine-Repola 2009				
S_{res}		*(0.10)*[1]	*(0.70)*	*(0.60)*	*(0.61)*	*(0.14)*[1]	*0.110*	*0.361*	*0.476*	*0.784*	*0.138*
7	9	8.5	1.0	1.7	0.3	11.5	8.2	0.9	0.6	0.4	10.2
15	15	59.0	6.0	5.9	4.6	75.6	55.4	6.9	3.3	2.2	69.4
30	25	388.2	38.7	33.0	33.1	493.1	309.7	37.8	11.4	10.2	374.3

[1] Values in parentheses are residuals when the Manning model is used with our data, that is use of D^2H as the only independent variable for all components with OLS on our data

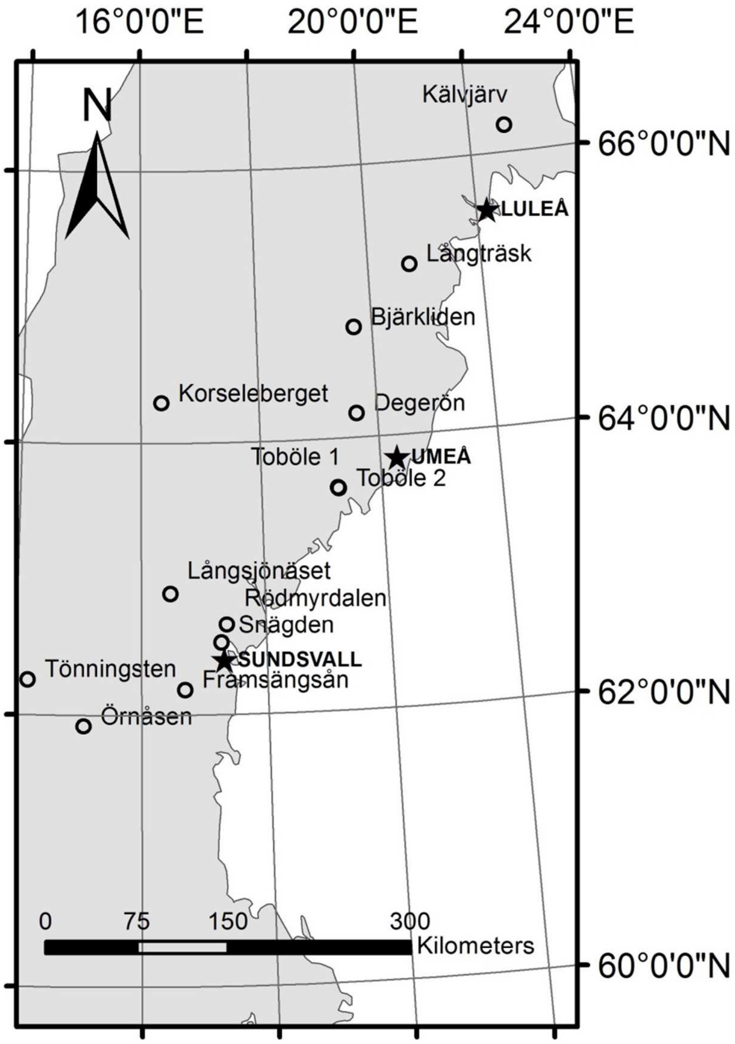
16°0'0"E
20°0'0"E
24°0'0"E
N
Kälvjärv
66°0'0"N
LULEÅ
Långträsk
Bjärkliden
Korseleberget
Degerön
64°0'0"N
Toböle 1
UMEÅ
Toböle 2
Långsjönäset
Rödmyrdalen
Snägden
SUNDSVALL
Tönningsten
Framsängsån
62°0'0"N
Örnåsen
0
75
150
300
Kilometers
60°0'0"N

Fig. 1

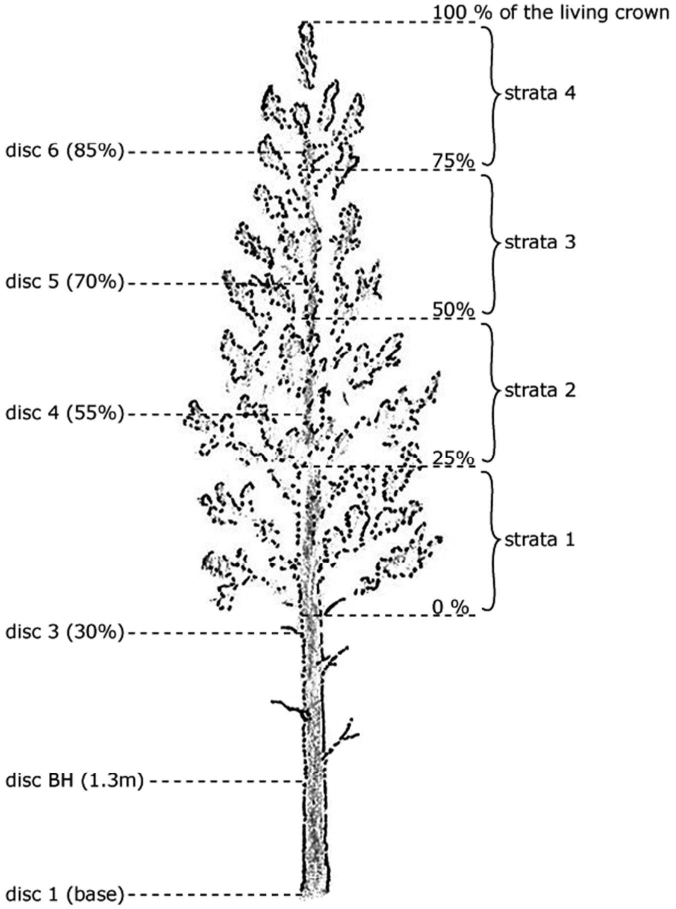
100 % of the living crown
strata 4
disc 6 (85%)
75%
strata 3
disc 5 (70%)
50%
strata 2
disc 4 (55%)
25%
strata 1
0 %
disc 3 (30%)
disc BH (1.3m)
disc 1 (base)

Fig. 2

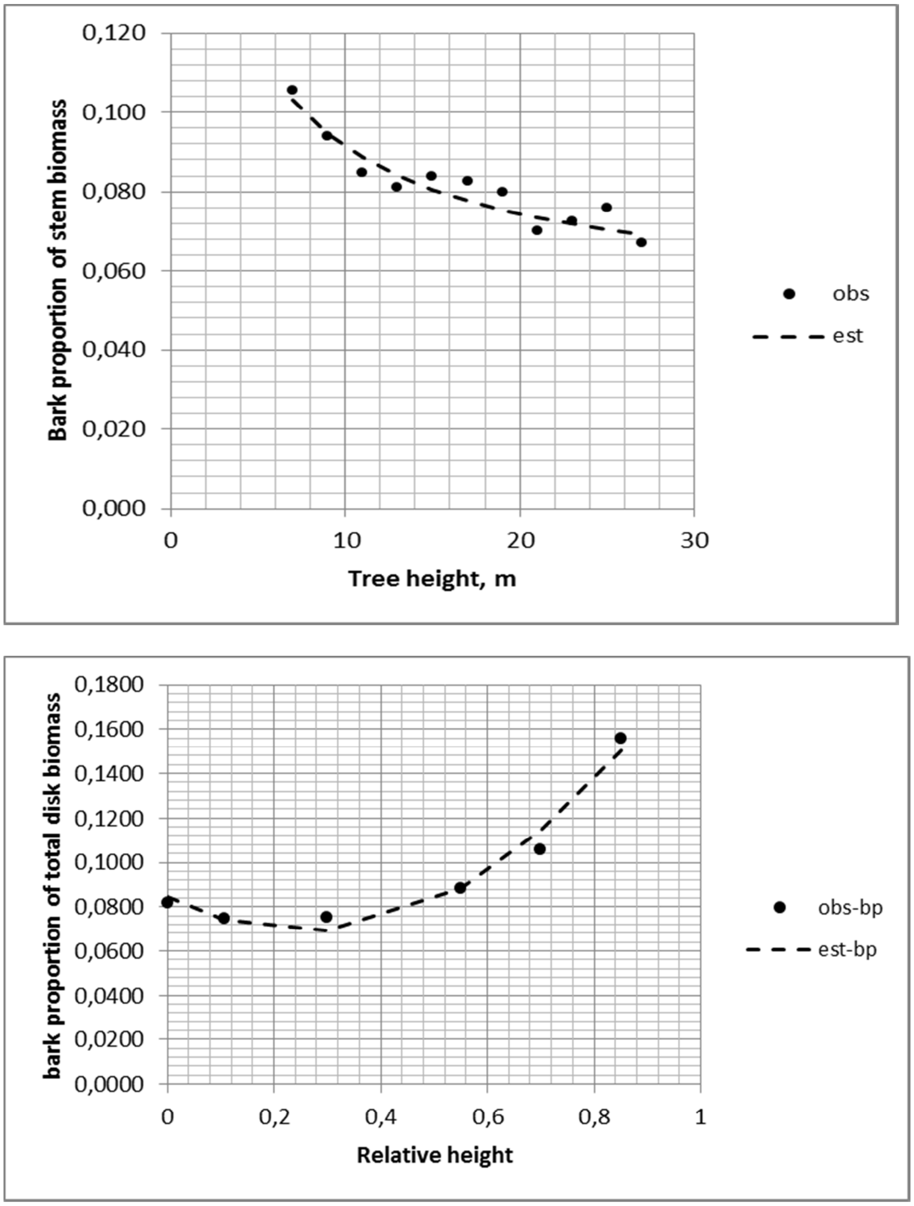
0,120
0,100
0,080
0,060
0,040
0,020
0,000
Bark proportion of stem biomass
0
10
20
30
Tree height, m
obs
est
0,1800
0,1600
0,1400
0,1200
0,1000
0,0800
0,0600
0,0400
0,0200
0,0000
bark proportion of total disk biomass
0
0,2
0,4
0,6
0,8
1
Relative height
obs-bp
est-bp

Fig. 3

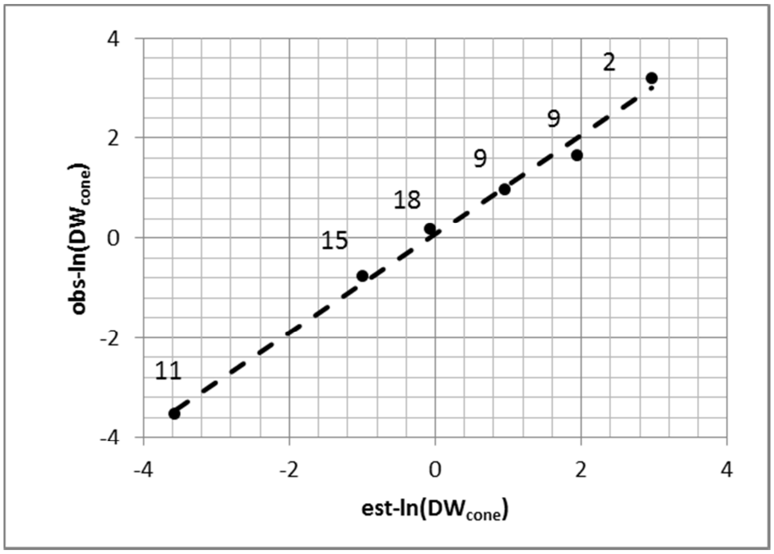

Fig. 4

Draft