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Biomass functions for Scots pine, Norway spruce and birch in Finland

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Abstract
In this study, biomass models for the above- and belowground tree components of Scots pine (Pinus sylvestris), Norway spruce (Picea abies [L.] Karst) and birch (Betula pendula and Betula pupescens) were compiled, and complementary equations developed for average stem density. The models were based on 1684 sample trees collected in 101 stands located on mineral soil sites, comprising 41 pine, 36 spruce and 24 birch stands. The study material consisted of subjectively selected experiments and temporary sample plots representing a wide range of stand and site conditions in Finland.
The models were estimated for individual tree components: stem wood, stem bark, living and dead branches, foliage, stump, and roots. A linear mixed model technique was applied in analyzing the data, and logarithmic transformation was used to convert the model to a linear form. Two model sets were developed. The simple models were mainly based on tree diameter and height, and the full models on all the variables measured in the Finnish national forest inventory.
The generalization and applicability of the models may be restricted by the fact that the study material was not an objective, representative sample of the tree stands in Finland, and some tree components (stump and roots and birch foliage) were poorly represented. Despite these shortcomings, the models provided uniform biomass predictions for a number of tree components, apart from stump and root biomass for pine, and were comparable with other functions used in Finland and Sweden (Hakkila 1972, 1979, 1991, Marklund 1988, Petersson 1999, 2006).

Keywords
tree biomass, biomass functions, biomass of tree components, wood density, pine, spruce, birch

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Other information

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1 Introduction

Tree biomass is usually divided into components according to their physiological functions, i.e. roots, stump, stem and crown. Direct measurement of the tree biomass, usually expressed as dry weight, is a time-consuming and expensive process. Therefore several allometric regression functions have been developed for tree biomass or its components based on easily measurable variables such as diameter at breast height, height, age and living crown length. Independent stand level variables such as altitude, site index, and north coordinate have also been used (Marklund 1988).

Several studies have been carried out on tree biomass in the Nordic countries, but only a few functions have been published that are based on a large material and which also include the main above and belowground tree components, such as stem, stem bark, living and dead branches, foliage, stump and roots. Marklund (1988) published biomass functions for different components on the basis of a large material from the Swedish national forest inventory, and these functions are widely used in the Nordic Countries. In Finland there is a lack of general biomass models in which different biomass components are modelled on the basis of the same material. Hakkila (1972, 1979, 1991) compiled separate biomass models for stems, crowns and stump and roots. Hakkila’s (1979) dry weight tables for pine, spruce and birch stems are based on a large, representative material collected as a part of the 5th National Forest Inventory (1968-1972). These tables provide estimates of stem biomass including bark as a function of tree diameter, height, and taper class. Hakkila’s (1991) models for crown biomass were primarily compiled for assessing the crown mass removed in harvesting, and not for the total growing stock.

Kärkkäinen (2005) investigated the performance of tree-level biomass models in Finland. The analysis was based on the properties of the data sets used and on the nature of the model predictions. The main comparison was made between Marklund's (1988) models based on breast height diameter and tree height, and a set of Hakkila's (1979, 1991) models based on a more extensive range of independent variables. Kärkkäinen (2005) concluded that Marklund's (1988) models were more applicable than Hakkila's (1979, 1991) because the data were the most representative: the models for different biomass components were derived from the same sample trees. Kärkkäinen (2005) also pointed out that the models for foliage and branch biomasses were the most unreliable of Marklund's (1988) models using diameter and height as independent variables.

The aim of this study is to develop biomass equations that effectively utilize the whole tree information produced by the National Forest Inventory (NFI). The models are developed for above- and belowground tree components of Scots pine, Norway spruce and birch, and also include complementary equations for average stem density.

2 Material

The study material consisted of a total of 101 stands: 41 Scots pine (Pinus sylvestris), 36 Norway spruce (Picea abies [L.] Karst.) and 24 birch stands (Betula pendula and Betula pubescens). The stands were mainly located on mineral soil sites representing a large part of Finland (Fig. 1). The average annual effective temperature sum (dd, >5ºC) varied between 705 and 1385 dd (Table 1). The stands were even-aged, and ranged from young to mature growing stock (Table 1). The spruce and birch stands were growing on fertile or highly fertile sites, and the pine stands on dry to fertile sites.

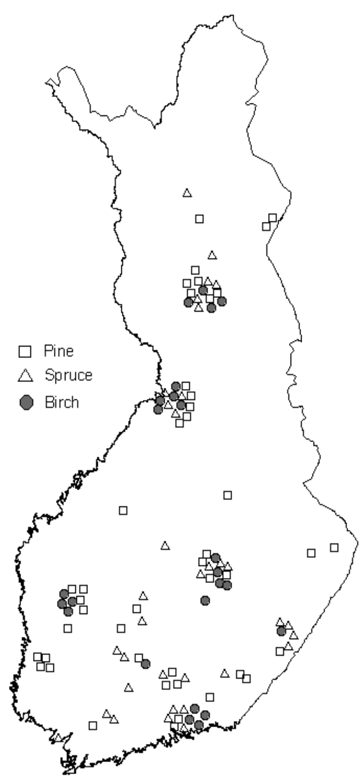

Figure 1. Location of the study stands.

Table 1. Range of stand characteristics by tree species.

	Number of stands	Temp. sum, dd	T, year	G, m^2ha^{-1}	D, cm	H, m
Scots pine	44	705-1314	13-145	1.0-32.5	3.7-32.4	3.2-26.4
Norway spruce	36	715-1385	18-161	2.2-48.1	4.2-35.0	3.3-31.4
Birch	24	818-1300	11-97	2.7-32.3	4.2-30.2	4.8-26.0

dd = cumulative annual temperature sum with a +5 ºC threshold, T = stand age (at stump height), G = stand basal area, D = mean diameter at breast height (weighted with tree basal area), H = mean height (weighted with tree basal area)

The study material consisted of 53 temporary sample plots, as well as control plots from 39 fertilization experiments and 9 thinning experiments. In the thinning experiments the sample trees were taken from unthinned, moderate and heavily thinned plots. The sample trees, mainly 4-5 trees per plot, represented the whole growing stock, but were selected by weighting by tree size. The total number of sample trees was 908, 613 and 127 for pine, spruce and birch, respectively (Table 2). Damaged trees were not accepted as sample trees. The majority of the sample trees were from the control plots of fertilization experiments (Table 2). The diameter and age distribution of the sample trees was broad, the diameter ranging between 1.5 and 41.7 cm (Table 3).

Table 2. Number of sample trees per experiment.

	Total	Temporary plot	Thinning experiment	Fertilization experiment
Scots pine	908	78	36	794
Norway spruce	613	67	24	522
Birch	127	85	42	-
Total	1648	230	102	1316

Table 3. Sample tree characteristics.

Variable	Scots pine			Norway spruce			Birch		
	Mean	Std	Range	Mean	Std	Range	Mean	Std	Range
Diameter, cm	13.1	5.3	1.5-35.8	17.9	7.2	1.7-41.7	16.5	7.0	2.5-38.0
Height, m	11.2	4.0	2.0-28.6	15.9	6.0	2.1-35.0	17.1	6.2	3.9-29.0
Age[1]	56	23.7	11-146	52	21.7	15-164	44	21.5	11-134
Crown ratio (0-1)	0.55	0.12	0.18-0.90	0.68	0.13	0.21-0.98	0.58	0.14	0.29-0.96
Radial growth[2], cm	0.54	0.33	0.04-2.03	0.76	0.41	0.07-2.48	0.75	0.58	0.05-3.47
Bark thickness[3], cm	1.5	1.1	0.1-7.4	1.1	0.63	0.2-4.1	0.9	0.48	0.2-2.8

[1]Age measured at stump height, [2]Breast height radial increment during the last five years, [3]Double bark thickness at breast height.

The field measurements were carried out between 1983 and 2003. Tree age, height, living crown length, stem diameter and bark thickness at six points along the stem, and diameter increment during the last five years (i_5) were measured on each tree. Sample disks were taken at breast height and at a height of 70% for stem biomass determination.

The living crown was divided into four sections of equal length, and one living sample branch was selected subjectively from each section. One dead sample branch per tree was taken from the lowest crown section. All the remaining branches in the crown section were cut off and divided into living and dead branches. The fresh weight of the branches by the sections was determined in the field. The sample branches were taken to the laboratory for fresh and dry weight determination.

The stump and root biomass were measured on a sub-sample of the trees on the temporary plots. The minimum coarse root diameter varied from 2-5 cm depending on tree diameter. In addition, the root biomass was determined on roots with a diameter larger than 1 cm on some of the trees. The fresh weight of the stump and roots were determined in the field. One sample (stump sector) was taken from the stump and two root discs for moisture content determination.

3 Methods

3.1 Biomass estimation for the sample trees

The biomass was estimated by individual tree components; stem wood, stem bark, living and dead branches, foliage, stump and roots. The branch biomass included both branch wood and bark, and the living branch biomass included cones. Not all the biomass components were measured on all the sample trees (Table 4).

Table 4. Number of measured biomass components by tree species.

	Scots pine	Norway spruce	Birch
Stem wood	626	366	127
Stem bark	311	170	127
Living branch	892	611	127
Dead branch	892	609	127
Foliage	892	611	21
Stump	36	31	39
Roots: > 2-5 cm	35	31	39
> 1 cm	6	5	6

The branch biomass of the tree was predicted by applying ratio estimation methods. The ratio of the dry and fresh weight of the sample branches was used to estimate the branch and needle dry weight from the fresh mass. Ratio estimates for living branch biomass were calculated first by crown sections. The total living branch biomass was the sum of the crown sections. A constant moisture content, based on the mean moisture content of dead sample branches on the plots, was used for dead branches.

The basic density (kgm-3) of two sample disks (breast height and a height of 70%) was determined in the laboratory, and the biomass of stem wood calculated by multiplying the stem volume by the average stem wood density. Stem volume, both under-bark and over-bark, was calculated by applying Laasasenaho's (1982) taper curve equations calibrated with diameter measurements at six points along the stem. Owing to the risk of bias in the estimates of average wood density, which was determined on the basis of only two sample disks per tree, the average wood density was determined by applying equations for the vertical dependence of wood density (Repola 2006) and the two sample disks measurements and the stem taper curve. Repola's (2006) equations were calibrated with the measurements made on the two disks in order to obtain the tree level density curve, which depicted the wood density at different points along the stem. The corresponding stem diameters, which were used as a weight in estimating the average wood density, were obtained from the taper curve. The average wood density was then calculated from the density curve and taper curve.

The biomass of stem bark was obtained from the average bark density and bark volume of the tree. The bark volume of the stem was calculated as the difference between the under-bark and over-bark stem volume. Bark volume was based on measured bark dimensions of the sample discs. The average bark density of the tree was the mean of the bark density measurements made on the two sample disks (breast height and a height of 70%). Disk level bark density was obtained by dividing the bark dry mass by the bark volume.

The stump and root biomass material (31-39 trees depending on the tree species) was collected from the temporary plots. The minimum coarse root diameter varied from 2-5 cm depending on the tree diameter. In addition, the root biomass of six trees of each tree species was determined on roots with a diameter larger than 1 cm. The >1 cm root biomass was estimated for the whole root material by applying the following simple regression equations:

Scots pine	y = 0.103+1.525x	$R^2 = 0.99$, $\hat{\sigma} = 1.471$ kg
Norway spruce	y = 0.842+1.306x	$R^2 = 0.99$, $\hat{\sigma} = 2.332$ kg
Birch	y =1.068+1.364 x	$R^2 = 0.99$, $\hat{\sigma} = 1.698$ kg

where y is the >1 cm root biomass and x the coarse root biomass (minimum root diameter 2-5 cm). The stump and root biomasses of the tree were estimated by applying ratio estimation methods based on the moisture content of the samples and the measured fresh weight of the roots and stump.

3.2 Model approaches

The biomass functions have a multiplicative model form. Logarithmic transformation was used to obtain homoscedastic variance, and to transform the model to a linear form. The wood density models were estimated in arithmetic units utilizing a linear model form. A linear mixed model technique was applied in analyzing the hierarchical data structure. The fertilization and thinning experiments were 3-level structured (stand, plot, tree) and the temporary plots 2-level structured (stand, tree). To define the model we treat the stand as a level 2 unit (between stands) and the tree (within stand) as a 1 level unit. In order to simplify the structure of the data the plot level was ignored in the fertilization experiments, and in the thinning experiments the plots were assumed to be independent. The final structure of the model was:

$$\ln(y_{ki}) = \mathbf{x}_{ki}^T\mathbf{b} + u_k + e_{ki} \tag{1}$$

where

- $\ln(y_{ki})$ = logarithm biomass of tree i in stand k
- $\mathbf{x}_{ki}$ = vector of the fixed regressors for tree i in stand k
- $\mathbf{b}$ = vector of fixed effects
- u_k = random effect for stand k
- e_{ki} = random effect for tree i in stand k

The dependent variable was logarithmically transformed in order to obtain homogeneous variance. When applying the models, a variance correction term, $(\mathrm{var}(u_k) + \mathrm{var}(e_{ki})/2)$ should be added to the intercept to correct for bias due to the logarithmic transformation. For dead branches, this correction factor tended to lead to an overestimation owing to the unsymmetrical distribution and the large variance in random parameters $(\mathrm{var}(u_k) + \mathrm{var}(e_{ki}))$. An unbiased correction can be performed for dead branches by applying an empirical correction term $c = \frac{\sum y}{\sum e^{\ln(\hat{y})}}$, where y is the measured biomass of the dead branches, and $\hat{y}$ is the fixed prediction for the logarithmic scale of dead branches. The unbiased prediction on the arithmetic scale is $\hat{y} = e^{\ln(\hat{y})} \cdot c$.

The equations of the tree components and total tree biomass were fitted separately. Models were compiled for the total aboveground tree biomass and for the following tree components:
- Stem wood
- Stem bark
- Living branch (including cones)
- Foliage
- Dead branches
- Stump
- Roots with diameter > 1 cm

and stem density for
- Stem wood density without bark
- Stem density with bark

4 Results

4.1 Biomass models

4.1.1 General

In model formulation the most significant independent variable, diameter at breast height, was substituted for stump diameter, d_S, using the following approximation, $d_S = 2+1.25d_{13}$ (Laasasenaho 1982). This was done in order to obtain a logical model form that is independent of tree size. The best transformation of diameter was $d_S/(d_S + n)$ (see also Marklund 1988), which did not lead to overestimates for large trees.

Two model sets were developed. 1a) The simple models were mainly based on tree diameter and height, and for some tree components (dead branches, birch foliage, stump and roots) only on diameter. 1b) Models were also compiled for the living branches and foliage that were based, in addition to diameter and height, on the living crown length. 2) The full models were based, in addition to diameter, height, and crown length (cl), on variables such as tree age (t_{13}), radial increment (i_5), and bark thickness (bt), which are variables that are also usually measured in the Finnish national forest inventory. The full models were compiled only for aboveground biomass components. Only a simple model was compiled for stump and root biomass in which tree diameter was an independent variable. The model for birch roots was improved by adding tree height.

4.1.2 Simple models

a) Simple models based on tree diameter and height

Scots pine

Aboveground biomass equations:

Stem wood: $$\ln(y_{ki}) = b_0 + b_1 \frac{d_{Ski}}{(d_{Ski}+14)} + b_2 \frac{h_{Ski}}{(h_{Ski}+12)} + u_k + e_{ki} \quad (2)$$

Stem bark: $$\ln(y_{ki}) = b_0 + b_1 \frac{d_{Ski}}{(d_{Ski}+12)} + b_2 \ln(h_{ki}) + u_k + e_{ki} \quad (3)$$

Living branches: $\ln(y_{ki}) = b_0 + b_1 \frac{d_{Ski}}{(d_{Ski}+12)} + b_2 \frac{h_{ki}}{(h_{ki}+12)} + u_k + e_{ki}$ (4)

Needles: $\ln(y_{ki}) = b_0 + b_1 \frac{d_{Ski}}{(d_{Ski}+6)} + b_2 \frac{h_{ki}}{(h_{ki}+1)} + u_k + e_{ki}$ (5)

Dead branches: $\ln(y_{ki}) = b_0 + b_1 \frac{d_{Ski}}{(d_{Ski}+16)} + u_k + e_{ki}$ (6)

Total (aboveground): $\ln(y_{ki}) = b_0 + b_1 \frac{d_{Ski}}{(d_{Ski}+12)} + b_2 \frac{h_{ki}}{(h_{ki}+20)} + u_k + e_{ki}$ (7)

Belowground biomass equations:

Stump: $\ln(y_{ki}) = b_0 + b_1 \frac{d_{Ski}}{(d_{Ski}+12)} + u_k + e_{ki}$ (8)

Roots >1 cm: $\ln(y_{ki}) = b_0 + b_1 \frac{d_{Ski}}{(d_{Ski}+8)} + u_k + e_{ki}$ (9)

Where

y_{ki} = biomass component or total biomass for tree i in stand k, kg
$d_{Ski} = 2 + 1.25\, d_{ki}$ (d_{ki} = tree diameter at breast height for tree i in stand k), cm
h_{ki} = tree height for tree i in stand k, m

Table 5. Estimates of the fixed and random parameters for the aboveground biomass of Scots pine (Equations 2-7). Standard error of the parameter estimate is presented in parentheses. The empirical correction factor (c) for the models for dead branches is also given.

	Stem wood Eq. 2	Stem bark Eq. 3	Living branches Eq. 4	Needles Eq. 5	Dead branches Eq. 6	Total Eq. 7
Fixed	N = 626	N = 311	N = 892	N = 892	N = 892	N = 285
b_0	-3.778	-4.756	-6.024	-5.007	-5.334	-3.215
	(0.032)	(0.110)	(0.093)	(0.594)	(0.175)	(0.059)
b_1	8.294	8.616	15.289	15.066	10.789	9.764
	(0.111)	(0.409)	(0.287)	(0.383)	(0.300)	(0.189)
b_2	4.949	0.277	-3.202	-5.896	-	2.889
	(0.112)	(0.088)	(0.320)	(0.893)		(0.188)
Random						
$\text{var}(u_k)$	0.002	0.013	0.033	0.097	0.271	0.001
$\text{var}(e_{ki})$	0.008	0.054	0.096	0.123	0.327	0.013
c					1.242	

Table 6. Estimates of the fixed and random parameters for the belowground biomass of Scots pine (Equations 8-9). Standard error of the parameter estimate is presented in parentheses.

	Stump Eq. 8	Roots > 1 cm Eq. 9
Fixed	N = 36	N = 35
b_0	-6.739	-9.601
	(0.183)	(0.223)
b_1	12.658	15.931
	(0.302)	(0.322)
Random		
$\mathrm{var}(u_k)$	0.009	0.000
$\mathrm{var}(e_{ki})$	0.044	0.065

Norway spruce

Aboveground biomass equations:

Stem wood: $\ln(y_{ki}) = b_0 + b_1 \frac{d_{Ski}}{(d_{Ski}+14)} + b_2 \ln(h_{ki}) + b_3 h_{ki} + +u_k + e_{ki}$ (10)

Stem bark: $\ln(y_{ki}) = b_0 + b_1 \frac{d_{Ski}}{(d_{Ski}+18)} + b_2 \ln(h_{ki}) + u_k + e_{ki}$ (11)

Living branches: $\ln(y_{ki}) = b_0 + b_1 \frac{d_{Ski}}{(d_{Ski}+13)} + b_2 \frac{h_{ki}}{(h_{ki}+5)} + u_k + e_{ki}$ (12)

Needles: $\ln(y_{ki}) = b_0 + b_1 \frac{d_{Ski}}{(d_{Ski}+10)} + b_2 \frac{h_{ki}}{(h_{ki}+1)} + u_k + e_{ki}$ (13)

Dead branches: $\ln(y_{ki}) = b_0 + b_1 \frac{d_{Ski}}{(d_{Ski}+18)} + \ln(h_{ki}) + u_k + e_{ki}$ (14)

Total (aboveground): $\ln(y_{ki}) = b_0 + b_1 \frac{d_{Ski}}{(d_{Ski}+20)} + b_2 \ln(h_{ki}) + u_k + e_{ki}$ (15)

Belowground biomass equations:

Stump: $\ln(y_{ki}) = b_0 + b_1 \frac{d_{Ski}}{(d_{Ski}+26)} + u_k + e_{ki}$ (16)

Roots >1 cm: $\ln(y_{ki}) = b_0 + b_1 \frac{d_{Ski}}{(d_{Ski}+24)} + u_k + e_{ki}$ (17)

Where

y_{ki} = biomass component or total biomass for tree i in stand k, kg
d_{Ski} = 2 + 1.25 d_{ki} (d_{ki} = tree diameter at breast height for tree i in stand k), cm
h_{ki} = tree height for tree i in stand k, m

Table 7. Estimates of the fixed and random parameters for the aboveground biomass of Norway spruce (Equations 10-15). Standard error of the parameter estimate is presented in parentheses. The empirical correction factor (c) for the models for dead branches is also given.

	Stem wood Eq. 10	Stem bark Eq. 11	Living branches Eq. 12	Needles Eq. 13	Dead branches Eq. 14	Total Eq. 15
Fixed	N = 366	N = 170	N = 611	N = 611	N = 611	N = 166
b_0	-3.655	-4.349	-3.914	-2.394	-5.467	-1.729
	(0.077)	(0.099)	(0.129)	(0.738)	(0.239)	(0.059)
b_1	7.942	9.879	15.220	12.752	6.252	9.697
	(0.184)	(0.595)	(0.434)	(0.456)	(0.899)	(0.378)
b_2	0.907	0.274	-4.350	-4.470	1.068	0.398
	(0.061)	(0.123)	(0.447)	(1.076)	(0.209)	(0.077)
b_3	0.018	-	-	-	-	-
	(0.004)					
Random						
$\mathrm{var}(u_k)$	0.006	0.016	0.022	0.103	0.256	0.004
$\mathrm{var}(e_{ki})$	0.008	0.036	0.089	0.107	0.335	0.015
c					1.181	

Table 8. Estimates of the fixed and random parameters for the belowground biomass of Norway spruce (Equations 16-17). Standard error of the parameter estimate is presented in parentheses.

	Stump Eq. 16	Roots > 1 cm Eq. 17
Fixed	N = 31	N = 31
b_0	-3.962	-2.295
	(0.248)	(0.336)
b_1	11.725	10.649
	(0.575)	(0.754)
Random		
$\mathrm{var}(u_k)$	0.065	0.105
$\mathrm{var}(e_{ki})$	0.058	0.114

Birch

Aboveground biomass equations:

Stem wood: $$\ln(y_{ki}) = b_0 + b_1 \frac{d_{Ski}}{(d_{Ski}+12)} + b_2 \ln(h_{ki}) + u_k + e_{ki} \quad (18)$$

Stem bark: $$\ln(y_{ki}) = b_0 + b_1 \frac{d_{Ski}}{(d_{Ski}+12)} + b_2 \frac{h_{ki}}{(h_{ki}+20)} + u_k + e_{ki} \quad (19)$$

Living branches: $$\ln(y_{ki}) = b_0 + b_1 \frac{d_{Ski}}{(d_{Ski}+16)} + b_2 \frac{h_{ki}}{(h_{ki}+10)} + u_k + e_{ki} \quad (20)$$

Foliage: $$\ln(y_{ki}) = b_0 + b_1 \frac{d_{Ski}}{(d_{Ski}+2)} + u_k + e_{ki} \quad (21)$$

Dead branches: $$\ln(y_{ki}) = b_0 + b_1 \frac{d_{Ski}}{(d_{Ski}+16)} + u_k + e_{ki} \quad (22)$$

Total (aboveground): $\ln(y_{ki}) = b_0 + b_1 \frac{d_{Ski}}{(d_{Ski}+12)} + b_2 \frac{h_{ki}}{(h_{ki}+22)} + u_k + e_{ki}$ (23)

Belowground biomass equations:

Stump: $\ln(y_{ki}) = b_0 + b_1 \frac{d_{Ski}}{(d_{Ski}+26)} + u_k + e_{ki}$ (24)

Roots >1 cm: $\ln(y_{ki}) = b_0 + b_1 \frac{d_{Ski}}{(d_{Ski}+22)} + \ln(h_{ki}) + u_k + e_{ki}$ (25)

Where

y_{ki} = biomass component or total biomass for tree i in stand k, kg
d_{Ski} = 2 + 1.25 d_{ki} (d_{ki} = tree diameter at breast height for tree i in stand k), cm
h_{ki} = tree height for tree i in stand k, m

Table 9. Estimates of the fixed and random parameters for the aboveground biomass of birch (Equations 18-23). Standard error of the parameter estimate is presented in parentheses. The empirical correction factor (c) for the models for dead branches is also given.

	Stem wood Eq. 18	Stem bark Eq. 19	Living branches Eq. 20	Foliage Eq. 21	Dead branches Eq. 22	Total Eq. 23
Fixed	N = 127	N = 127	N = 127	N = 21	N = 127	N = 127
b_0	-5.001	-5.449	-4.279	-29.566	-7.742	-3.662
	(0.069)	(0.157)	(0.240)	(3.881)	(1.152)	(0.057)
b_1	9.284	9.967	14.731	33.372	11.362	10.329
	(0.189)	(0.497)	(0.665)	(4.201)	(1.987)	(0.182)
b_2	1.143	2.894	-3.139	-	-	3.411
	(0.050)	(0.542)	(0.755)			(0.197)
Random						
$\text{var}(u_k)$	0.003	0.011	0.035	0	1.034	0.001
$\text{var}(e_{ki})$	0.005	0.044	0.071	0.077	2.705	0.007
c					2.245	

Table 10. Estimates of the fixed and random parameters for the belowground biomass of birch (Equations 24-25). Standard error of the parameter estimate is presented in parentheses.

	Stump Eq. 24	Roots > 1 cm Eq. 25
Fixed	N = 39	N = 39
b_0	-3.677	-3.183
	(0.244)	(0.490)
b_1	11.537	7.204
	(0.553)	(0.923)
b_2	-	0.892
		(0.289)
Random		
$\text{var}(u_k)$	0.021	0.047
$\text{var}(e_{ki})$	0.046	0.027

b) Models for crown components based on diameter, height and living crown length

Scots pine

Living branches: $\ln(y_{ki}) = b_0 + b_1 \dfrac{d_{Ski}}{(d_{Ski}+12)} + b_2 \dfrac{h_{ki}}{(h_{ki}+8)} + b_3 \ln(cl_{ki}) + u_k + e_{ki}$ (26)

Needles: $\ln(y_{ki}) = b_0 + b_1 \dfrac{d_{Ski}}{(d_{Ski}+4)} + b_2 \dfrac{h_{ki}}{(h_{ki}+1)} + b_3 \ln(cl_{ki}) + u_k + e_{ki}$ (27)

Norway Spruce

Living branches: $\ln(y_{ki}) = b_0 + b_1 \dfrac{d_{Ski}}{(d_{Ski}+14)} + b_2 \dfrac{h_{ki}}{(h_{ki}+5)} + b_3 \ln(cl_{ki}) + u_k + e_{ki}$ (28)

Needles: $\ln(y_{ki}) = b_0 + b_1 \dfrac{d_{Ski}}{(d_{Ski}+4)} + b_2 \dfrac{h_{ki}}{(h_{ki}+1)} + b_3 \ln(cl_{ki}) + u_k + e_{ki}$ (29)

Birch

Living branches: $\ln(y_{ki}) = b_0 + b_1 \dfrac{d_{Ski}}{(d_{Ski}+12)} + b_2 \dfrac{h_{ki}}{(h_{ki}+12)} + b_3 cl_{ki} + u_k + e_{ki}$ (30)

Foliage: $\ln(y_{ki}) = b_0 + b_1 \dfrac{d_{Ski}}{(d_{Ski}+2)} + b_2 cr_{ki} + u_k + e_{ki}$ (31)

Where

y_{ki} = biomass component or total biomass for tree i in stand k, kg
d_{Ski} = 2 + 1.25 d_{ki} (d_{ki} = tree diameter at breast height for tree i in stand k), cm
h_{ki} = tree height for tree i in stand k, m cl = length of living crown, m
cl_{ki} = length of living crown for tree i in stand k, m
cr_{ki} = crown ratio for tree i in stand k, 0-1

Table 11. Estimates of the fixed and random parameters for the aboveground biomass of birch (Equations 26-31). Standard error of the parameter estimate is presented in parentheses.

	S. pine living branches Eq. 26	S. pine needles Eq. 27	N. spruce living branches Eq. 28	N. spruce needles Eq. 29	Birch living branches Eq. 30	Birch Foliage Eq. 31
Fixed	N = 892	N = 892	N = 611	N = 611	N = 127	N = 21
b_0	-5.224	-2.385	-2.945	0.286	-4.837	-20.856
	(0.087)	(0.524)	(0.123)	(0.592)	(0.191)	(4.015)
b_1	13.022	15.022	12.698	16.286	13.222	22.320
	(0.270)	(0.460)	(0.418)	(0.788)	(0.628)	(4.628)
b_2	-4.867	-11.979	-6.183	-15.576	-4.639	2.819
	(0.286)	(0.802)	(0.414)	(1.056)	(0.589)	(0.795)
b_3	1.058	1.116	0.959	1.170	0.135	
	(0.054)	(0.065)	(0.076)	(0.081)	(0.016)	
Random						
$\mathrm{var}(u_k)$	0.020	0.034	0.013	0.021	0.013	0.011
$\mathrm{var}(e_{ki})$	0.067	0.095	0.072	0.090	0.054	0.044

4.1.3 Full models

Scots pine

Aboveground biomass equations:
Stem wood:

$$\ln(y_{ki}) = b_0 + b_1 \frac{d_{Ski}}{(d_{Ski}+9)} + b_2 \frac{h_{ki}}{(h_{ki}+16)} + b_3 t_{13ki} + b_4 i_{g5ki} + u_k + e_{ki} \quad (32)$$

Stem bark:

$$\ln(y_{ki}) = b_0 + b_1 \frac{d_{Ski}}{(d_{Ski}+8)} + b_2 \frac{d_{ki}}{t_{13ki}} + b_3 bt_{ki} + u_k + e_{ki} \quad (33)$$

Living branches:

$$\ln(y_{ki}) = b_0 + b_1 \frac{d_{Ski}}{(d_{Ski}+10)} + b_2 \frac{h_{ki}}{(h_{ki}+4)} + b_3 \ln(i_{g5ki}) + b_4 \ln(cl_{ki}) + u_k + e_{ki} \quad (34)$$

Needles:

$$\ln(y_{ki}) = b_0 + b_1 \frac{d_{Ski}}{(d_{Ski}+6)} + b_2 \frac{h_{ki}}{(h_{ki}+1)} + b_3 \ln(i_{g5ki}) + b_4 \ln(cl_{ki}) + u_k + e_{ki} \quad (35)$$

Dead branches:

$$\ln(y_{ki}) = b_0 + b_1 \frac{d_{Ski}}{(d_{Ski}+16)} + b_2 \ln(cl_{ki}) + b_3 \ln(i_{g5ki}) + b_4 t_{13ki} + u_k + e_{ki} \quad (36)$$

Total (aboveground):

$$(y_{ki}) = b_0 + b_1 \frac{d_{Ski}}{(d_{Ski}+12)} + b_2 \frac{h_{ki}}{(h_{ki}+18)} + b_3 i_{5ki} + b_4 t_{13ki} + b_5 bt_{ki} + u_k + e_{ki} \quad (37)$$

Where

y_{ki} = biomass component or total biomass for tree i in stand k, kg
d_{Ski} = 2 + 1.25 d_{ki} (d_{ki} = tree diameter at breast height for tree i in stand k), cm
h_{ki} = tree height for tree i in stand k, m
cl_{ki} = length of living crown for tree i in stand k, m
t_{13ki} = tree age at breast height for tree i in stand k
bt_{ki} = double bark thickness at breast height for tree i in stand k, cm
i_{5ki} = breast height radial increment during the last five years for tree i in stand k, cm
i_{g5ki} = breast height cross-sectional area increment during the last five years for tree i in stand k, cm^2

Table 12. Estimates of the fixed and random parameters for the aboveground biomass of Scots pine (Equations 32-37). Standard error of the parameter estimate is presented in parentheses. The empirical correction factor (c) for the models for dead branches is also given.

	Stem wood Eq. 32	Stem bark Eq. 33	Living branches Eq. 34	Needles Eq. 35	Dead branches Eq. 36	Total Eq. 37
Fixed	N =586	N = 274	N = 791	N = 791	N = 652	N = 251
b_0	-4.660	-5.672	-4.755	-1.928	-5.890	-3.342
	(0.051)	(0.171)	(0.137)	(0.564)	(0.206)	(0.065)
b_1	8.686	9.809	12.923	9.456	17.351	9.353
	(0.130)	(0.262)	(0.334)	(0.454)	(0.787)	(0.206)
b_2	4.896	-0.442	-5.111	-6.867	-0.623	3.344
	(0.113)	(0.111)	(0.357)	(0.858)	(0.147)	(0.214)
b_3	0.003	0.070	0.069	0.281	-0.422	0.134
	(0.0003)	(0.015)	(0.021)	(0.025)	(0.059)	(0.025)
b_4	0.002	-	0.927	0.709	-0.016	0.001
	(0.0004)		(0.062)	(0.071)	(0.003)	(0.0004)
b_5	-	-	-	-	-	-0.014
						(0.007)
Random						
$\mathrm{var}(u_k)$	0.001	0.008	0.019	0.027	0.153	0.001
$\mathrm{var}(e_{ki})$	0.008	0.055	0.061	0.082	0.318	0.010
c					1.192	

Norway spruce

Aboveground biomass equations:
Stem wood:

$$\ln(y_{ki}) = b_0 + b_1 \frac{d_{Ski}}{(d_{Ski}+12)} + b_2 \ln(h_{ki}) + b_3 h_{ki} + b_4 t_{13ki} + b_5 i_{5ki} + u_k + e_{ki} \quad (38)$$

Stem bark:

$$\ln(y_{ki}) = b_0 + b_1 \frac{d_{Ski}}{(d_{Ski}+16)} + b_2 \ln(h_{ki}) + b_3 bt_{ki} + u_k + e_{ki} \quad (39)$$

Living branches:

$$\ln(y_{ki}) = b_0 + b_1 \frac{d_{Ski}}{(d_{Ski}+18)} + b_2 \frac{h_{ki}}{(h_{ki}+2)} + b_3 cr_{ki} + b_4 \frac{d_{ki}}{t_{13_{ki}}} + b_5 i_{5ki} + u_k + e_{ki} \quad (40)$$

Needles:

$$\ln(y_{ki}) = b_0 + b_1 \frac{d_{Ski}}{(d_{Ski}+12)} + b_2 cr_{ki} + b_3 \ln(i_{5ki}) + u_k + e_{ki} \quad (41)$$

Dead branches:

$$\ln(y_{ki}) = b_0 + b_1 \frac{d_{Ski}}{(d_{Ski}+14)} + b_2 \ln(cr_{ki}) + b_3 cr_{ki} + b_4 \ln(i_{5ki}) + u_k + e_{ki} \quad (42)$$

Total (aboveground):

$$\ln(y_{ki}) = b_0 + b_1 \frac{d_{Ski}}{(d_{Ski}+20)} + b_2 \ln(h_{ki}) + b_3 cr_{ki} + u_k + e_{ki} \quad (43)$$

Where

y_{ki} = biomass component or total biomass for tree i in stand k, kg
d_{Ski} = 2 + 1.25 d_{ki} (d_{ki} = tree diameter at breast height for tree i in stand k), cm
h_{ki} = tree height for tree i in stand k, m
cr_{ki} = crown ratio for tree i in stand k, 0-1
t_{13ki} = tree age at breast height for tree i in stand k
bt_{ki} = double bark thickness at breast height for tree i in stand k, cm
i_{5ki} = breast height radial increment during the last five years for tree i in stand k, cm

Table 13. Estimates of the fixed and random parameters for the aboveground biomass of Norway spruce (Equations 38-43). Standard error of the parameter estimate is presented in parentheses. The empirical correction factor (c) for the models for dead branches is also given.

	Stem wood Eq. 38	Stem bark Eq. 39	Living branches Eq. 40	Needles Eq. 41	Dead branches Eq. 42	Total Eq. 43
Fixed	N = 365	N = 164	N = 567	N = 584	N = 578	N = 164
b_0	-3.918	-4.540	-3.126	-4.362	0.574	-1.972
	(0.068)	(0.098)	(0.334)	(0.167)	(1.467)	(0.124)
b_1	8.515	9.574	13.160	9.249	11.455	9.240
	(0.212)	(0.619)	(0.346)	(0.172)	(0.384)	(0.420)
b_2	0.693	0.249	-2.800	1.050	3.558	0.519
	(0.060)	(0.122)	(0.519)	(0.127)	(0.987)	(0.092)
b_3	0.027	0.092	1.457	0.276	-7.901	0.246
	(0.003)	(0.029)	(0.123)	(0.028)	(1.534)	(0.111)
b_4	0.002	-	-0.856	-	-0.194	-
	(0.0005)		(0.143)		(0.060)	
b_5	-0.057	-	0.187	-	-	-
	(0.019)		(0.056)			
Random						
$\mathrm{var}(u_k)$	0.003	0.009	0.004	0.019	0.199	0.005
$\mathrm{var}(e_{ki})$	0.008	0.038	0.071	0.071	0.266	0.014
c					1.059	

Birch

Aboveground biomass equations:
Stem wood:

$$\ln(y_{ki}) = b_0 + b_1 \frac{d_{Ski}}{(d_{Ski}+12)} + b_2 \ln(h_{ki}) + b_3 \frac{d_{ki}}{t_{13ki}} + u_k + e_{ki} \quad (44)$$

Stem bark:

$$\ln(y_{ki}) = b_0 + b_1 \frac{d_{Ski}}{(d_{Ski}+8)} + b_2 \frac{h_{ki}}{(h_{ki}+22)} + b_3 \ln(bt_{ki}) + u_k + e_{ki} \quad (45)$$

Living branches:

$$\ln(y_{ki}) = b_0 + b_1 \frac{d_{Ski}}{(d_{Ski}+10)} + b_2 \frac{h_{ki}}{(h_{ki}+10)} + b_3 \ln(i_{5ki}) + b_4 cl_{ki} + b_5 t_{13ki} + u_k + e_{ki} \quad (46)$$

Dead branches:

$$\ln(y_{ki}) = b_0 + b_1 \frac{d_{Ski}}{(d_{Ski}+6)} + b_2 \frac{h_{ki}}{(h_{ki}+10)} + b_3 t_{13ki} + b_4 i_{5ki} + u_k + e_{ki} \qquad (47)$$

Total (aboveground):

$$\ln(y_{ki}) = b_0 + b_1 \frac{d_{Ski}}{(d_{Ski}+12)} + b_2 \frac{h_{ki}}{(h_{ki}+22)} + b_3 i_{5ki} + b_4 \frac{d_{ki}}{t_{13ki}} + u_k + e_{ki} \qquad (48)$$

Where

y_{ki} = biomass component or total biomass for tree i in stand k, kg
d_{Ski} = 2 + 1.25 d_{ki} (d_{ki} = tree diameter at breast height for tree i in stand k), cm
h_{ki} = tree height for tree i in stand k, m
cl_{ki} = crown length for tree i in stand k, m
t_{13ki} = tree age at breast height for tree i in stand k
bt_{ki} = double bark thickness at breast height for tree i in stand k, cm
i_{5ki} = breast height radial increment during the last five years for tree i in stand k, cm

Table 14. Estimates of the fixed and random parameters for the aboveground biomass of birch (Equations 44-48). Standard error of the parameter estimate is presented in parentheses. The empirical correction factor (c) for the models for dead branches is also given.

	Stem wood Eq. 44	Stem bark Eq. 45	Living branches Eq. 46	Dead branches Eq. 47	Total Eq. 48
Fixed	N = 127	N = 127	N = 124	N = 124	N = 124
b_0	-4.969	-4.885	-5.155	-15.998	-3.733
	(0.060)	(0.377)	(0.220)	(2.038)	(0.052)
b_1	9.593	7.858	11.910	36.138	10.473
	(0.188)	(0.680)	(0.678)	(6.021)	(0.163)
b_2	1.087	3.525	-3.369	-16.483	3.546
	(0.056)	(0.500)	(0.620)	(4.810)	(0.184)
b_3	-0.172	0.497	0.241	-0.050	0.113
	(0.045)	(0.079)	(0.045)	(0.014)	(0.003)
b_4	-	-	0.117	-1.389	-0.335
			(0.015)	(0.425)	(0.068)
b_5	-	-	0.010		-
			(0.002)		
Random					
$\mathrm{var}(u_k)$	0.001	0.008	0.009	0.591	0.000
$\mathrm{var}(e_{ki})$	0.005	0.036	0.043	2.540	0.006
c				1.925	

4.2 Comparison between simple and full models

The simple and full models were not directly comparable because the full models were based on a smaller number of observations owing to missing measurements for the independent variables. In general, however, the addition of independent variables to the models reduced the between-stand variance more than the within-stand variance for all the aboveground tree components. The addition of independent variables to the models for stem biomass based on diameter and height reduced only the between-stand variance. Adding tree age and variables depicting the tree growth rate to the model for stem wood biomass decreased the error variance by 10%, 21% and 25% for pine, spruce and birch, respectively. The addition of bark thickness (bt) as an independent variable improved the bark models for all the tree species, and the error variance was reduced by 6-20%. The simple models for the living branches and foliage were significantly improved by adding crown length (cl) to the model. In the needle model the between-stand variance decreased by 65% for pine and 80% for spruce, and the within-stand variance decreased by 20% for both tree species. The random variance was further decreased by about 20% by adding radial increment (i5) to the needle models. Crown length and radial increment improved the model for living branches, but the decrease in random variance was less than that in the needle models.

4.3 Models for stem wood density

Regression equations were constructed to predict the average density of stem with bark and without bark. The equations were based mainly on tree diameter and tree age.

Stem wood density without bark

Scots pine: $y_{ki} = b_0 + b_1 \frac{d_{ki}}{t_{13ki}} + b_2 dd_k + u_k + e_{ki}$ (49)

Norway spruce: $y_{ki} = b_0 + b_1 d_{Ski} + b_2 \frac{d_{ki}}{t_{13ki}} + u_k + e_{ki}$ (50)

Birch: $y_{ki} = b_0 + b_1 \ln(d_{Ski}) + b_2 \frac{d_{ki}}{t_{13ki}} + u_k + e_{ki}$ (51)

Stem density including bark

Scots pine: $y_{ki} = b_0 + b_1 \frac{d_{ki}}{t_{13ki}} + b_2 dd_k + u_k + e_{ki}$ (52)

Norway spruce: $y_{ki} = b_0 + b_1 d_{Ski} + b_2 \frac{d_{ki}}{t_{13ki}} + u_k + e_{ki}$ (53)

Birch: $y_{ki} = b_0 + b_1 \ln(d_{Ski}) + b_2 \frac{d_{ki}}{t_{13ki}} + u_k + e_{ki}$ (54)

Where

y_{ki} = Stem density for tree i in stand k, kgm^{-3}
d_{ki} = tree diameter at breast height for tree i in stand k, cm
d_{Ski} = 2 + 1.25 d_{ki}, cm
t_{13ki} = tree age at breast height for tree i in stand k
dd = average temperature sum in sand k

Table 15. Estimates of the fixed and random parameters for the average stem density of Scots pine, Norway spruce and birch (Equations 49-54). Standard error of the parameter estimate is presented in parentheses.

	Scots pine. Eq. 49	Scots pine. Eq. 52	N. spruce. Eq. 50	N. spruce. Eq. 53	Birch, Eq. 51	Birch, Eq. 54
Fixed	N = 593	N = 262	N = 366	N = 166	N = 127	N = 127
b_0	374.61	378.39	447.77	442.03	396.74	431.43
	(7.979)	(12.002)	(5.980)	(7.009)	(19.147)	(19.723)
b_1	-98.272	-78.829	-0.659	-0.904	37.234	28.054
	(8.087)	(10.768)	(0.184)	(0.198)	(6.478)	(6.641)
b_2	0.066	0.039	-101.84	-82.695	-67.086	-52.203
	(0.007)	(0.011)	(10.411)	(13.288)	(14.029)	(14.430)
Random						
$\text{var}(u_k)$	25.879	51.006	90.55	73.69	136.67	133.88
$\text{var}(e_{ki})$	566.24	556.38	640.46	524.74	551.41	610.47

4.4 Comparison with other functions

The predictions of the equations constructed in this study were compared with those of Hakkila's (1972, 1979, 1991), Marklund's (1988) and Petersson's (1999, 2006) functions. The comparisons were made among the equations for living crown (needles and branches), stem (stem wood and bark) and belowground (stump and roots) biomass, and primarily those equations based on tree diameter and height. In addition, the biomass components were predicted by applying the full models. Sample trees from the 9th Finnish National Forest Inventory (1996-2003) were used as a test material.

Stem biomass was estimated as the sum of the results of the stem wood and bark biomass equations. Hakkila's (1979) dry weight tables included stem wood and bark. The differences in the results given by the equations for pines with a diameter under 30 cm were minor. The compiled functions (simple and full model) yielded lower stem biomass values for pines with a diameter over 30 cm than those given by Marklund's (1988) and Hakkila's (1979) functions (Figure 2). For spruce, Marklund's function resulted in the highest stem biomass, and Hakkila's and the developed functions gave almost similar results. For birch stem biomass all the functions gave relatively similar results.

The most significant differences in stem biomass were for trees with a large diameter, which may partly be caused by the fact that the functions were applied outside their validity range. The maximum diameter in our data was 35 cm for pine, 42 cm for spruce and 38 cm for birch. The maximum validity limits of Marklund's (1988) functions for pine, spruce and birch are broader, 45, 50 and 35cm, respectively. Hakkila's (1979) dry weight tables are valid up to 40 cm. It should be kept in mind that the reliability of the predictions is usually the lowest in the lower and upper bounds of modelling data. These comparisons were made for functions in which only the stem form variation caused by varying tree breast height diameter and height was taken into account. Stem form variation – independently from variation of the breast height diameter and height – had strong influence on tree volume and stem biomass. Tree stem form especially in southern Sweden may deviate from that of our material.

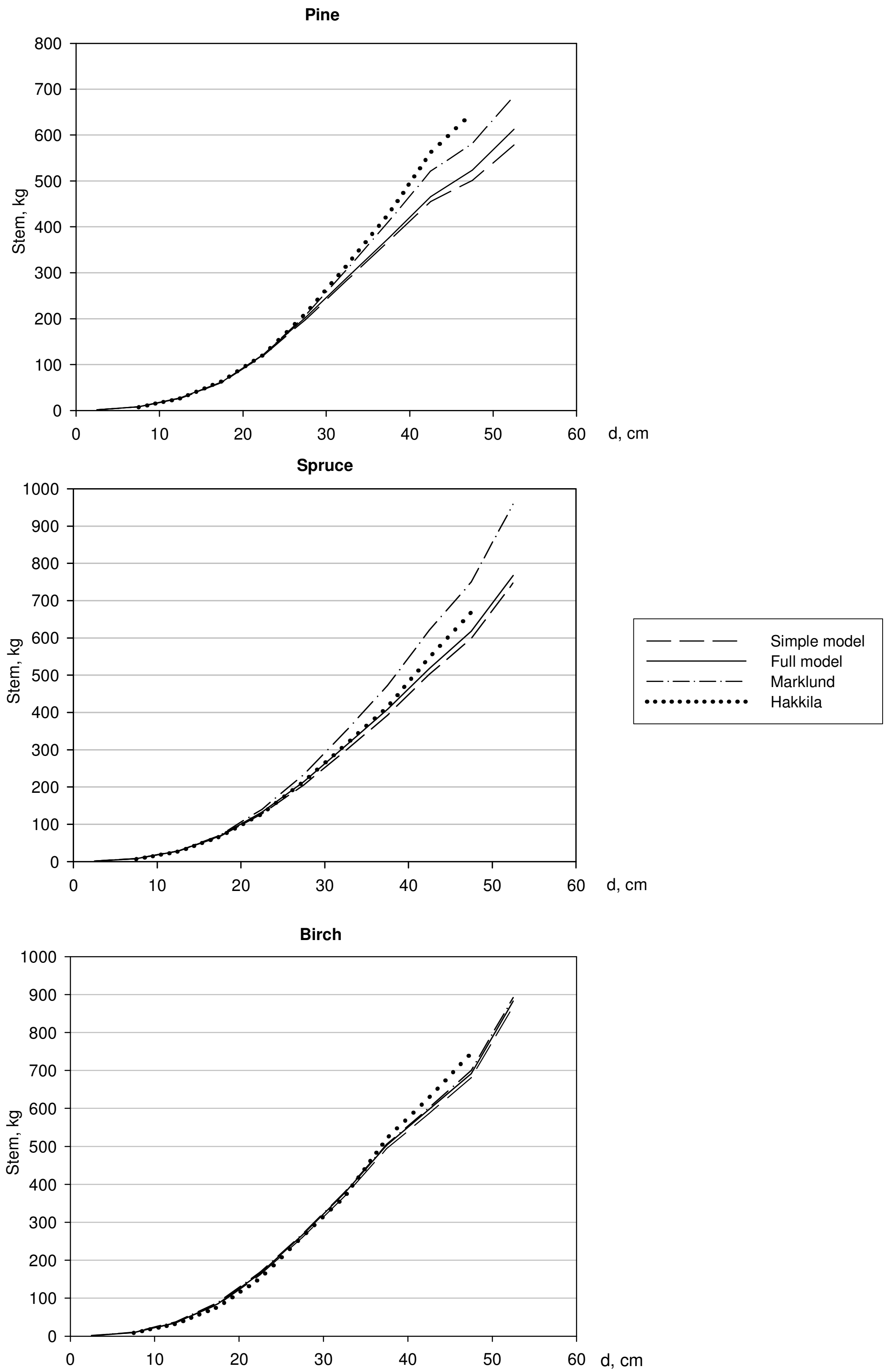

Figure 2. The expected stem biomass in the Finnish NFI data predicted using different biomass functions.

The living crown biomass was calculated using Hakkila's (1991) and Marklund's (1988) functions, which include both branches and needles for pine and spruce, but only branches for birch. In addition, Petersson's (1999) function was applied to predict the branch and foliage biomass for birch. The crown biomass in our study was defined as the sum of the equations for living branches and needles or foliage.

Hakkila's function clearly gave the largest living crown biomass for pine and spruce with a diameter of over 30 cm (Figure 3). The compiled and Marklund's functions gave a similar prediction for large trees. The simple model gave the highest crown biomass for pine and the full model the lowest crown biomass for spruce (Figure 3). For birch trees with a diameter under 25 cm, all the functions gave a relatively similar result, but with a diameter above 25 cm the deviation was larger, and Marklund's function clearly gave the lowest crown biomass. The results were not directly comparable because Hakkila's and Marklund's functions do not include foliage and, in addition to diameter and height, Marklund's equation was based on north coordinates, and Petersson's function (1999) based on tree diameter and radial growth during the last five years. The deviation between the results for large trees may be a consequence of a lack of large trees in the study materials and the model form used. For example, Hakkila's functions are applicable for trees at the harvesting stage.

The compiled models (simple models) for the belowground biomass were compared to Hakkila's (1972), Marklund's (1988) and Petersson's (2006) functions based on only tree diameter. Comparison of the belowground biomass components, i.e. stump and roots, is not directly comparable because the minimum root diameter varies among the studies. In our study, root biomass was determined up to a diameter of 1 cm. Hakkila's functions predict biomass for the stump and roots with a diameter of over 5 cm, and they cannot be applied for trees under 10 cm in diameter. Marklund's belowground biomass was calculated using two functions, one for the stump and one for roots with a diameter of over 5 cm. Petersson's functions included stump and roots down to a diameter of 5 mm. Marklunds's and Petersson's functions for pine and spruce were mainly based on the same large material, but the function for birch (Petersson 2006) was based on only 13 sample trees. The Swedish functions (Marklund 1988, Petersson 2006) clearly gave higher belowground, stump and root biomass for pine compared to the Finnish functions (Figure 4). The results obtained with the compiled and of Hakkila's function were relatively similar, but the compiled equations gave an unexpectedly lower biomass when the minimum root diameter was taken into account. Petersson's function resulted in the highest stump and root biomass for all tree species, and followed a logical pattern compared to that of Marklund's functions. The compiled functions gave a relatively similar belowground biomass for spruce and 15-20% lower values for birch compared to the results obtained with Petersson's functions.

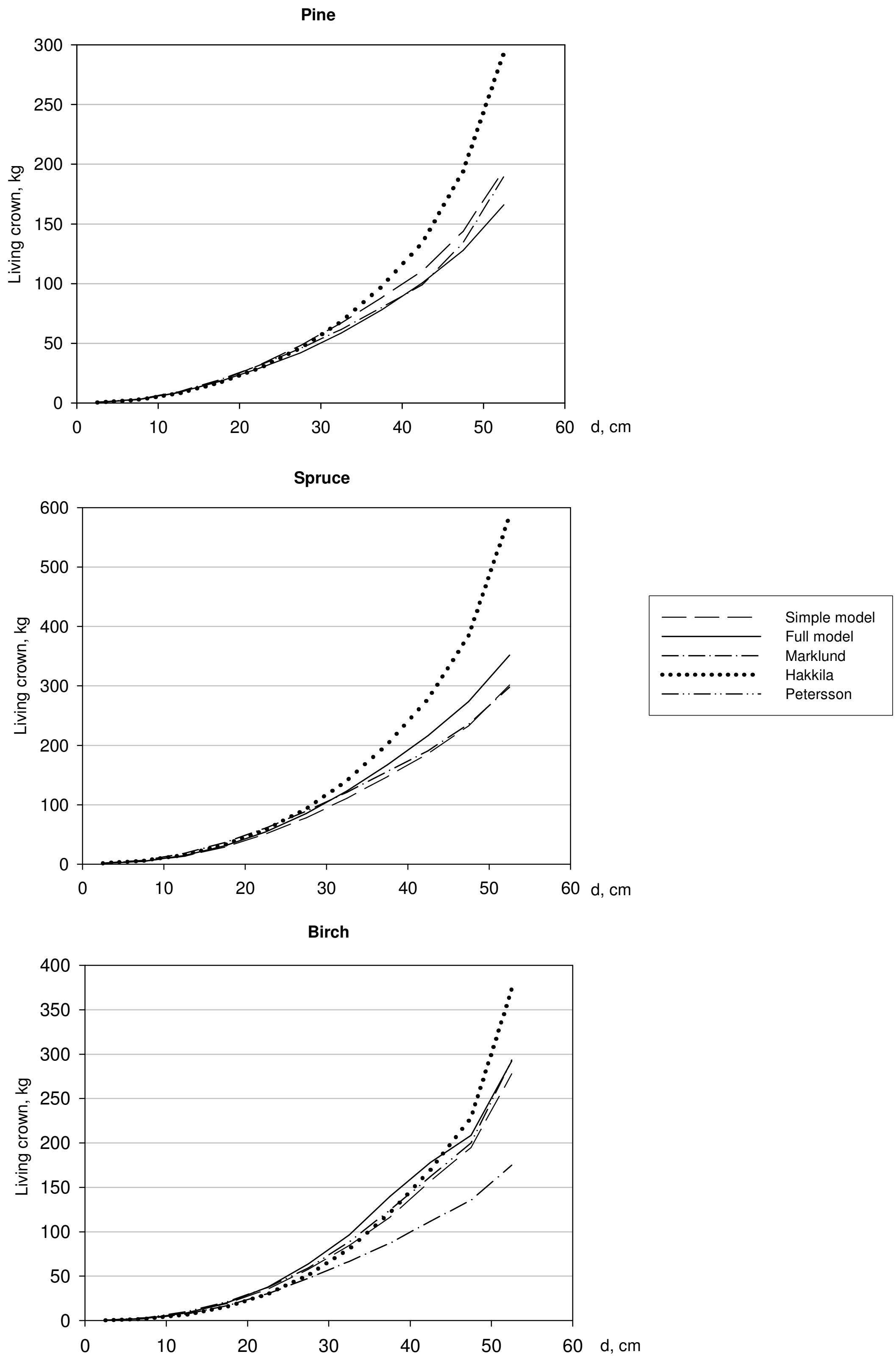

Figure 3. The expected living crown biomass in the NFI data predicted using different biomass functions.

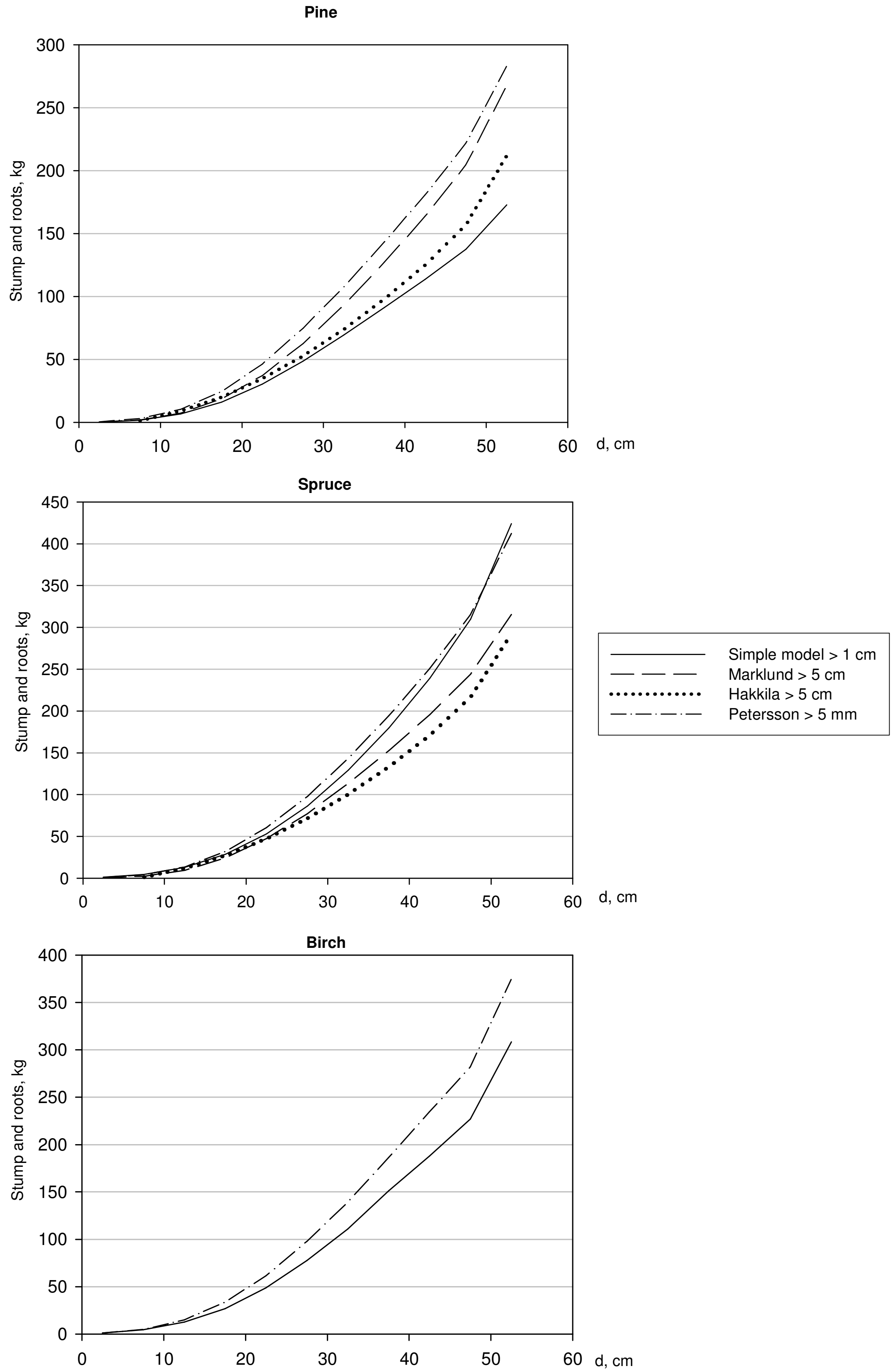

Figure 4. The stump and root biomass in the NFI data predicted using different biomass functions.

5 Discussion

The compiled biomass equations for individual trees are applicable over a large part of Finland. However, in the northernmost parts of Finland, in coastal areas and on peatlands the validity of the functions is uncertain due to the lack of material. The new functions are applicable to all growing stock, and are valid over a wide diameter range up to 35, 42 and 38 cm for pine, spruce and birch, respectively. The models were formulated so that the predictions would be logical throughout the range of the material, and even in cases where the functions were extrapolated. There may be problems when the tree height is under 1.3m. In order to partly eliminate this problem, we used the approximated stump diameter (d_S=2+1.25d) instead of tree diameter. The best expression of diameter in the models was d_S/d_S+n, which tended not to produce an overestimation for large trees and behaved more logically in the extrapolation compared to the generally used transformation for tree diameter, $ln(d)$ (See Marklund 1988). However, special care should be taken when applying the function outside its validity limits.

All the aboveground tree components were relatively well represented in the material, apart from birch foliage. The model for birch foliage was based on only 21 sample trees, and it is valid over a narrower diameter range from 12 to 26 cm. Similarly, the belowground biomass equations were based on deficient material. In addition, the biomass of roots >1 cm was measured on only a few trees per tree species, and for the rest of the root material it was estimated using simple regression. These facts should be kept in mind when applying the model for root biomass, especially for trees with a diameter of under 5 cm or over 25 cm, and for trees growing on peatlands where the root biomass is usual higher than that on mineral soil (Hakkila 1972, Marklund 1988).

The models were based on subjectively selected experiments and temporary sample plots, concentrated especially in southern Finland. Although the study material was selected from a wide range of stand and site conditions, it was not an objective, representative sample of all the stands in Finland, and this may restrict the generalization and applicability of the models. The pine material represented relatively well the average tree variables on mineral soil in South Finland (NFI9). In contrast, the birch and spruce trees in the study material were growing faster than the average for southern Finland (according to the 9th NFI). Due to the lack of representative material, except for some tree components, the models based only on tree diameter are therefore not presented here, and some recommendations for suitable applications of the compiled models need to be set (Appendix 1).

In the model application, there is a risk of systematic prediction error resulting from a lack of representative material if the simple models are applied to stands where the distribution of tree characteristics deviates from that of the study material. This risk can be decreased by applying the full models to stands on mineral soil and peatlands.

For crown components, i.e. living branches and foliage, the most applicable and stable prediction was obtained by using the equations based on diameter, height and a crown variable (crown ratio or crown length). The crown variable diminished the between-stand error variance by 65% for pine and 80% for spruce. This indicates significantly better predictions for the stand level crown biomass. This will also improve the prediction for energy wood stocks, where Marklund's (1988) models based on diameter and height seem to be the most unreliable (Kärkkäinen 2005). The crown models were slightly improved by adding tree age and growth as independent variables, but this also increased the multicollinearity of the independent variables, which subsequently increased the risk of biased prediction in the combination of independent variables that were poorly represented in the study material. Application of the simple model based only on tree diameter and height can lead to biased predictions for the crown components in northern Finland and on peatlands, especially on undrained mires, where the diameter-height relationship deviates from that of the study material.

There are two alternatives ways to predict stem biomass. One way is to apply the models that directly predict stem biomass. These models are valid for trees of all sizes, as well as for trees with a height under 6m, but they do not take into account stem form, which has a strong influence on tree volume and also on stem biomass. When measured upper diameters and applicable volume function are available, stem volume can be calculated more accurately. In such a case it is recommended to estimate stem biomass using the models for average wood density. Stem volume can be converted into biomass by multiplying the predicted stem density by the volume.

For belowground components, the compiled equations for spruce and birch were applicable, but the model for pine obviously underestimated the stump and root biomass. In order to obtain more reliable prediction of the belowground biomass of pine, it is recommended to use Marklund's (1988) or Petersson's (2006) functions.

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Appendix 1. Recommendations about where to apply the equations. The equation number is given.

Scots pine	Mineral soils Southern Finland	Mineral soils Northern Finland	Peatlands Southern Finland	Peatlands Northern Finland
Stem wood and bark	52*	52*	52*	52*
Stem wood	2, 32, 49*	2, 32, 49*	2, 32, 49*	2, 32, 49*
Stem bark	3, 33	3, 33	3, 33	3, 33
Living branches	4, 26, 34	26, 34	26, 34	26, 34
Needles	5, 27, 35	27, 35	27, 35	27, 35
Dead branches	6, 36	6	6	6
Total aboveground	7, 37	7, 37	7, 37	7, 37
Stump	-	-	-	-
Roots	-	-	-	-

Norway spruce	Mineral soils Southern Finland	Mineral soils Northern Finland	Peatlands Southern Finland	Peatlands Northern Finland
Stem wood and bark	53*	53*	53*	53*
Stem wood	10, 38, 50*	10, 38, 50*	10, 38, 50*	10, 38, 50*
Stem bark	11, 39	11, 39	11, 39	11, 39
Living branches	12, 28, 40	12, 28	12, 28	12, 28
Needles	13, 29, 41	29, 41	29, 41	29, 41
Dead branches	14, 42	14	14	14
Total aboveground	15, 43	15, 43	15, 43	15, 43
Stump	16	16	16	16
Roots	17	17	17	17

Birch	Mineral soils Southern Finland	Mineral soils Northern Finland	Peatlands Southern Finland	Peatlands Northern Finland
Stem wood and bark	54*	54*	54*	54*
Stem wood	18, 44, 51*	18, 44, 51*	18, 44, 51*	18, 44, 51*
Stem bark	19, 45	19, 45	19, 45	19, 45
Living branches	20, 30, 46	20, 30, 46	30, 46	30, 46
Foliage	21, 31	31	31	31
Dead branches	22, 47	22	22	22
Total aboveground	23, 48	23, 48	23, 48	23, 48
Stump	24	24	24	24
Roots	25	25	25	25

* Stem biomass is recommended to estimate using the models for average wood density in the case, when measured upper diameters and applicable volume function are available.