Functions for Estimating Stem Diameter and Tree Age Using Tree Height, Crown Width and Existing Stand Database Information

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The aim was to investigate the relations between diameter at breast height and maximum crown diameter, tree height and other possible independent variables available in stand databases. Altogether 76 models for estimating stem diameter at breast height and 60 models for tree age were formulated using height and maximum crown diameter as independent variables. These types of models can be utilized in modern remote sensing applications where tree crown dimensions and tree height are measured automatically. Data from Finnish national forest inventory sample plots located throughout the country were used to develop the models, and a separate test site was used to evaluate them. The RMSEs of the diameter models for the entire country varied between 7.3% and 14.9% from the mean diameter depending on the combination of independent variables and species. The RMSEs of the age models for entire country ranged from 9.2% to 12.8% from the mean age. The regional models were formulated from a data set in which the country was divided into four geographical areas. These regional models reduced local error and gave better results than the general models.

The standard deviation of the dbh estimate for the separate test site was almost 5 cm when maximum crown width alone was the independent variable. The deviation was smallest for birch. When tree height was the only independent variable, the standard deviation was about 3 cm, and when both height and maximum crown width were included it was under 3 cm. In the latter case, the deviation was equally small (11%) for birch and Norway spruce and greatest (13%) for Scots pine.

Keywords forest inventory, crown diameter, stem diameter, modeling
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1 Introduction

The development of modern remote sensing sensors has increased the need to create new forest models (Maltamo et al. 2003). One of the most promising methods is to use high resolution digital aerial photographs (Pollock 1996, Gong et al. 2002, Korpela 2004, Wang et al. 2004) or laser scanning (Hyyppä et al. 2001, Holmgren 2003, Næsset 2004) to measure individual trees. As early as the 1970s, Jakobsons (1970) and Talts (1977) described the possibility of measuring the height of a tree, the crown diameter or even the diameter at breast height on aerial photographs by photogrammetry. However, these measurements usually only represent the dimensions of the crown as visible on the aerial photographs, the resolution and visibility of small branches and irregular crown parameters being dependent on the scale of the photograph. In theory, however, a close correlation exists in principle between crown diameter and stem characteristics, such as diameter at breast height, and the latter is also highly correlated with the photogrammetrically measured crown diameter, a relation for which Petlewitz (1976) observed a correlation coefficient of 0.9 in *Pinus silvestris* and a standard deviation of the regression of 2.5 cm. Klier (1970) emphasized the influence of scale, image quality, species and species mixture, while the close relationship between these variables motivated many researchers (e.g. Sayn-Wittenstein et al. 1967) to construct aerial tree and stand volume tables based on crown diameter. Such tables, based on stand height, crown closure and crown diameter as independent variables or in a modified form (Eid and Næsset 1998, Gingrich et al. 1955, Avery and Meyer 1959), are today in common use in North America and Norway.

Krajicek et al. (1961) studied relations of crown and diameter at breast height in open-grown trees not confounded by competition, measuring 340 such trees in eastern Iowa. The crown width of a tree in an open stand is closely related to its diameter at breast height, the correlation coefficient for every species being over 0.98. This relation was found to be independent of age and site quality, but differed slightly between tree species. Open-grown trees were shorter than forest-grown ones of the same diameter on similar soils and under similar conditions. This is attributed to competition between adjacent trees under forest conditions, a factor which also tends to reduce the size of the live crown, and especially the crown width.

Ilvessalo (1950) and Jakobsons (1970) studied the correlation between tree crown diameter and diameter at breast height under boreal managed forest conditions. Ilvessalo (1950) found that as branches are cloaked by adjacent trees, measurements of maximum crown diameter on photographs are generally smaller than those made on the ground. Also, crown diameter varies with tree species, tree height, site and stand density. The correlation between crown diameter and diameter at breast height was best for Scots pine and much weaker for Norway spruce. Jakobsons (1970) studied this correlation for pine, spruce and birch separately and reached the following conclusions for trees belonging to the same diameter (at breast height) class. Conifers have smaller crown diameters than deciduous trees, but the location of the tree is also important, such that trees in southern Sweden have greater crown diameters than those in the north. Meanwhile, trees on poor sites or in open stands have greater crown diameters than those on nutrient-rich sites or in denser stands. Jakobsons (1970) also found that an almost linear relation exists between crown diameter and diameter at breast height, although this differed between tree species and between geographically distant trees. The crown diameter of young trees was wider than that of older trees. The relation was also confounded by competition between trees, the availability of light and site factors. Jakobsons (1970) nevertheless maintained that it was possible to estimate diameter at breast height as a function of crown diameter. Talts (1977), by contrast, concluded that also other independent variables in addition to crown diameter were necessary.

Nash (1949) and Nyyssönen (1955) found a standard error of 0.6 m in crown diameter estimates on photographs, and Worley et al. (1955) obtained a standard error between 0.9 m and 1.2 m on 1:12 000 photographs. More recently, Hildebrandt (1996) reconstructed the dbh distribution of beech stands from the observed distribution of crown widths. Stand age can also be estimated from a regression equation with photogrammetrically determined stand height and crown size as the predictor variables, although because of the inherent uncertainties, a given stand is usually assigned to one of 20 year classes. Studies in Germany (see Van Laar and Akca 1997) have indicated that the age class of a stand can be estimated from photographic measurements.

New measuring methods, such as laserscanning (Hyyppä et al. 2001, Holmgren 2003, Næsset 2004) or digital photogrammetry (Korpela 2000, 2004); have specific characteristics and measurement techniques. Because imaging condition and applicability of tree measurements differ according to the distance to objects, the relative position of the tree and other similar factors, traditional photography-based crown diameter measurements are not a good basis for modelling. When allometric tree models are created using field measurement, separate calibration models can be used to relate photography-based measurements and ground measurements with improved accuracy. When models are applied directly without calibration using automatic segmentation, small trees are easily overestimated and large trees are underestimated (Ikonen 2004). This type of error can be reduced using calibration techniques which utilize imaging parameters and few field observations (Mäkinen 2004). The models can be directly applied, when laser scanning is used as a remote sensing technique. Tree volume can then be derived from these variables using a chain of models in which diameter at breast height is estimated first. The aim of this study was to investigate the relations between diameter at breast height and maximum crown diameter, tree height and other possible independent variables and to formulate models for estimating the diameter at breast height using different independent variables and chains of models. Models for tree age were also formulated, with height and maximum crown diameter as independent variables.

2 Material

The main material used in the present work was based on the 1889 permanent sample plots established throughout Finland for the purposes of the Finnish National Forest Inventory (NFI). Plot size varied according to diameter at breast height of a tree. Plot size was 100 m^2, when diameter was under 10.5 cm and otherwise 300 m^2. An additional data set (Korpela 2004), comprising 346 Scots pines, 245 Norway spruces and 120 birches on a site near the Hyytiälä Research Station, was used to validate the models.

The NFI sample plot network is based on cluster sampling, where each cluster in southern Finland includes four sample plots and each cluster in northern Finland three. The distance between two clusters is also greater in the north than in the south, as is the sample plot interval. The material contains data from the 1st and 3rd rounds of measurements made on the permanent sample plots (in 1985–86 and 1995).

The material includes only trees for which crown diameter measurements are available, and only the data for 1995 were used to formulate the models. The crown diameters in the NFI material were measured according to field instructions, i.e. by taking the widest dimension of the crown. Any obvious mistakes in measuring and recording the data were removed, leaving a total set of 11 246 trees. Trees have been classified according to their position in the stand into the following categories: dominant (63%), intermediate (33%), and suppressed (4%), which refer to determined relative height of tree, over 80 %, 50–80% and less than 50%, respectively. The locations of the clusters are presented in Fig. 1.

The material also includes damaged and diseased trees, which can exhibit a highly abnormal relation between diameter at breast height and either height or crown diameter, causing bias in the models. It is assumed that living trees can be identified by remote sensing material. This may not be the case if the top of the tree is broken or the tree is dying (barely any living canopy left). After removing these abnormal trees, the data used for the diameter at breast height and the age models comprised 5303 Scots pines, 3661 Norway spruces and 2282 birches. The average values for the sample tree and stand variables are presented in Table 1. A caliper was used to measure the diameter at breast height, a Suunto hypsometer to measure tree height, an increment borer to measure tree age and a Kajanus tube to measure crown width.

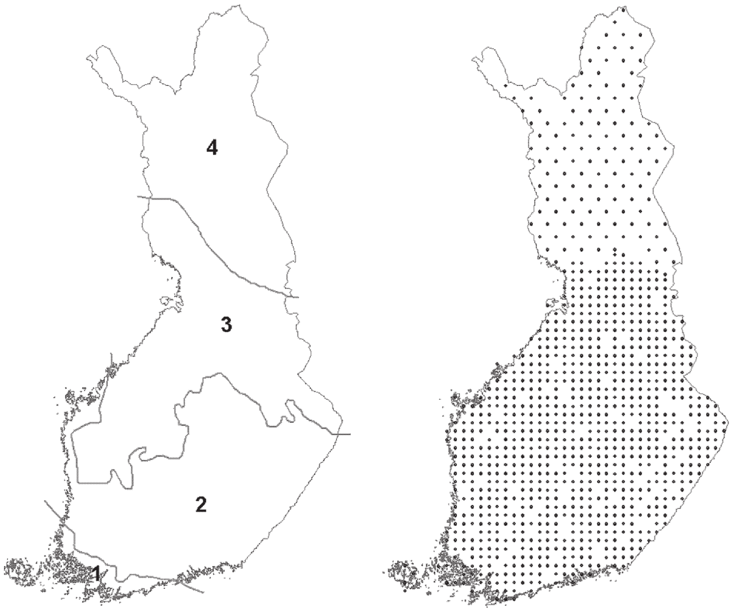

Fig. 1. Models were constructed for all of Finland (right side) and for four separate regions (left side). Geographical regions are defined by the forest flora and climatic conditions (1 = Hemiboreal, 2 = South boreal, 3 = Middle boreal, 4 = North boreal). The entire area is covered by clusters. The locations of the clusters are shown on the right side of the figure.

As the relations between tree variables may vary depending on the location (see Jakobsons 1970), the material for the entire country was divided into four geographical areas defined according to the forest flora and climatic conditions (Fig. 1). The resulting distribution is presented in Table 2.

3 Methods

Due to the hierarchical nature of the data, a mixed effect method with iterative generalized least squares (IGLS) was used for linearized regression. The independent variables were selected according to the requirements defined for the new forest inventory procedure, i.e. that all independent variables should be accessible from high resolution aerial photographs or existing databases. The photogrammetric variables were height, maximum crown diameter, stem number of dominant trees per hectare and relative tree height class. The photogrammetric variables and variables from the stand database were treated as independent variables in the regression model. The intercept was the only fixed effect of the basic model. Clusters and plots were treated as random effects. The form of model is

$$\boldsymbol{y} = \boldsymbol{Xb} + \boldsymbol{Zc} + \boldsymbol{e}$$
$$\Leftrightarrow y_{kji} = x_{kji}'\boldsymbol{b} + c_k + d_{kj} + e_{kji},$$

where $\boldsymbol{y}$ is an $n \times 1$ vector of observed values of the dependent variable, $\boldsymbol{b}$ is a $p \times 1$ vector of fixed parameters, $\boldsymbol{X}$ is an $n \times p$ matrix of independent variables associated with fixed parameters, $\boldsymbol{c}$ is a $q \times 1$ vector of random parameters with expectation zero, $\boldsymbol{Z}$ is an $n \times q$ matrix of explanatory variables associated with random parameters and $\boldsymbol{e}$ is an $n \times 1$ vector of error terms, $\boldsymbol{e} \sim N(0,\sigma^2)$. Furthermore, in this case, k is the cluster to which the tree i in the plot j belongs, c_k is the random parameters of cluster k and d_{kj} is the random parameters of plot j.

The variables (α) from existing stand databases

Table 1. Mean statistics of field material (NFI) by species.

	N	Mean	Sd	Min	Max
$D_{1,3}$, mm					
Pine	5303	145	69	4	574
Spruce	3661	148	78	4	515
Birch	2282	115	56	6	532
H, dm					
Pine	5303	113	47	14	286
Spruce	3661	123	59	14	318
Birch	2282	113	44	16	310
D_{crm}, dm*					
Pine	5303	31	12	4	101
Spruce	3661	33	12	6	95
Birch	2282	33	12	7	104
Age, years					
Pine	5303	59	34	11	297
Spruce	3661	66	31	12	278
Birch	2282	48	20	3	148
x, km	11246	3452	122	3117	3725
y, km	11246	7015	208	6650	7725
Altitude (alt), m	11246	127	65	0	410
Temperature sum (ts), °	11246	1100	164	531	1425
Basal area (ba), m^2/ha	11246	20.9	7.9	1	48
Mean diameter ($d_{1,3m}$), cm	11246	17.4	6.5	6	46
Mean age (age_m), years	11246	71.9	40.3	12	334
Number of trees/ha (n)	11246	1554	934	33	7067
Relative tree height class (dummy)	11246			0	1
Site class (dummy)	11246			0	1
Soil type (dummy)	11246			0	1
Land-use class (dummy)	11246			0	1

* D_{crm} refers to maximum crown diameter

Table 2. Number of trees of NFI field plots in different geographical areas.

	Pine	Spruce	Birch	Total
Area 1	129	104	39	272
Area 2	1840	2180	871	4891
Area 3	2641	1200	1190	5031
Area 4	693	177	182	1052

that were tested were similar to variables which can be found in the forest planning databases provided by private forest owners in Finland, together with a few generally accepted variables: x co-ordinate, y co-ordinate, height above sea level, temperature sum, mean diameter, mean age, tree class, basal area, land-use class, site class and soil type. Stand variables, which could be derived from an aerial photograph, such as stem number of dominant trees per hectare and relative tree height, were also tested. In general, dominant height is defined as the mean height of the 100 thickest trees at breast height in one hectare. In the context of this study only tree heights can be used to define dominant height because diameters are not known. Dominant tree is defined as a tree which height is more than 80 % from dominant height. Relative tree height could be estimated by comparing the height of the recognized tree to the dominant height of the recognized trees of the remote sensing material on a site. Relative tree height class is used as a dummy variable (D9). It indicates that a tree is suppressed or dominated defined as a tree which height is under 80 percent from dominant height, therefore differing from a dominant or emergent tree. A model with three variables (h, d_{crm}, α) was chosen for each tree species and area based on a log likelihood ratio test (Goldstein 1995) achieving the best coefficient of determination.

To meet the normality and homoscedaticity assumptions, square root and logarithm transformations were used for the independent and dependent variables.

The models for diameter at breast height were of the forms:

$$\sqrt{d_{1,3}} = f\left(\sqrt{h}\right) + \varepsilon \quad (1)$$

$$\sqrt{d_{1,3}} = f\left(\sqrt{d_{crm}}\right) + \varepsilon \quad (2)$$

$$\sqrt{d_{1,3}} = f\left(\sqrt{h}, \sqrt{d_{crm}}\right) + \varepsilon \quad (3)$$

$$\sqrt{d_{1,3}} = f\left(\sqrt{h}, \sqrt{d_{crm}}, \alpha\right) + \varepsilon \quad (4)$$

and the age models of the forms:

$$\ln(age) = f\left(\ln(h)\right) + \varepsilon \quad (5)$$

$$\ln(age) = f\left(\ln(d_{crm})\right) + \varepsilon \quad (6)$$

$$\ln(age) = f\left(\ln(h), \ln(d_{crm})\right) + \varepsilon \quad (7)$$

where
$d_{1,3}$ = diameter at breast height (mm),
h = height (dm),
d_{crm} = crown diameter, maximum (dm)
α = stand variable from database or aerial photograph

The models were used to estimate the value of the variable in its original unit of measurement. As non-linear transformations were used for the dependent variables, such an estimate will be biased (Lappi 1993), an effect that can be reduced by bias correction. Taking this into account, the model for diameter at breast height assumes the form

$$d_{1,3} = f(\;)^2 + \mathrm{var}(\varepsilon)$$

and the age model the form

$$age = \exp\left[f(\;)\right] * \left(1 + \frac{1}{2}\mathrm{var}(\varepsilon)\right)$$

R^2 was calculated separately to cluster, plot and tree effects, e.g. R^2 for plot indicates the proportion of variance between plots, that is explained by a model. Proportion of total variance between clusters and between plots are also presented. R^2 was calculated using a method described in Lappi (1997), where relation of estimated full mixed model variance and initial variance of random effect model of clusters and plots (the fixed part includes only a constant) were utilized as follows:

$$R^2 = 1 - \frac{\text{(estimated variance of full model)}}{\text{(initial variance of model)}}$$

The non-linear extra sum of squares method (Bates and Watts 1988) was used to evaluate the differences between the geographical areas. The method requires the fitting of full and reduced models. The full model corresponds to different sets of parameters for each of the geographical areas involved. The reduced model corresponds to the same set of parameters for all regions. The suitability of the division and the need for any division at all were assessed on the basis of the test results. The appropriate test statistic is described in Bates and Watts (1988).

4 Results

4.1 Data Analysis for Modelling

The normality and homoscedasticity of models were tested. As an example of a model that meets these assumptions well, the diameter of Scots pines at breast height in area 3 is presented in Fig. 2. There were about 2640 pines in the area.

Altogether 136 models were constructed. These were numbered using a system in which the first digit for a model defines the geographic area (Fig. 1) in question (number of the area or 9 as an indication of the entire country), the second digit the form of the model and the last the tree species. For example, model 2.2.3 applies to diameter

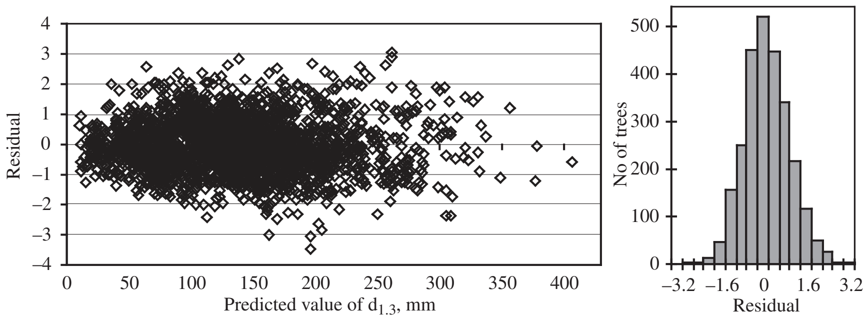

Fig. 2. Diagnostic testing of the model $d_{1,3} = f(h, d_{crm})$ for Scots pine in area 3. Residual plot in the left side and normality plot of residuals in the right side.

Table 3. Statistical properties of the models for the entire country. $\mathbf{R^2}$ is divided into cluster (Clus), plot (Plot) and tree (Tree) effects. Proportion of total variance (VAR%) is calculated for clusters and plots. The first digit in number of model refers to the geographic area (Fig. 1) in question (number of the area or 9 as an indication of the entire country), the second digit the form of the model and the last digit the tree species.

Model	No. of model	Predictor	RMSE %	RMSE mm	R^2 Clus	R^2 Plot	R^2 Tree	VAR% Clus	VAR% Plot	VAR
All	9.1.0	h	12.5	17.5	0.53	0.85	0.77	0.18	0.23	2.058
Pine	9.1.1	h	12.3	17.8	0.76	0.85	0.68	0.18	0.26	2.057
Spruce	9.1.2	h	10.1	15.0	0.24	0.94	0.86	0.26	0.23	1.408
Birch	9.1.3	h	13.1	15.0	0.31	0.83	0.73	0.30	0.26	1.854
All	9.2.0	d_{crm}	14.8	20.7	0.70	0.78	0.64	0.08	0.25	2.862
Pine	9.2.1	d_{crm}	13.0	18.8	0.75	0.75	0.72	0.16	0.39	2.309
Spruce	9.2.2	d_{crm}	14.9	22.1	0.39	0.84	0.63	0.10	0.28	3.056
Birch	9.2.3	d_{crm}	12.8	14.7	0.72	0.88	0.60	0.13	0.19	1.770
All	9.3.0	h, d_{crm}	9.8	13.8	0.67	0.91	0.86	0.21	0.22	1.269
Pine	9.3.1	h, d_{crm}	8.0	11.6	0.87	0.96	0.85	0.23	0.16	0.869
Spruce	9.3.2	h, d_{crm}	8.3	12.3	0.38	0.96	0.91	0.32	0.21	0.948
Birch	9.3.3	h, d_{crm}	9.6	11.0	0.65	0.93	0.82	0.28	0.19	1.000
All	9.4.0	h, d_{crm}, D9	9.3	13.0	0.73	0.92	0.87	0.19	0.21	1.141
Pine	9.4.1	h, d_{crm}, y	7.7	11.1	0.91	0.96	0.86	0.17	0.17	0.806
Spruce	9.4.2	h, d_{crm}, ts	7.3	10.8	0.80	0.96	0.91	0.13	0.26	0.738
Birch	9.4.3	h, d_{crm}, ts	8.8	10.1	0.84	0.92	0.84	0.16	0.25	0.838

model for birch in area 2 (tree species = 3), with the maximum diameter of the crown as the only independent variable (form of the model = 2). It should be noted that tree height and maximum crown diameter are expressed in decimetres in all the models, yielding the diameter at breast height in millimetres.

4.2 Models for Diameter at Breast Height

The data for all sample plots in the country were used to formulate the first set of models for diameter at breast height. General information on these models is given by tree species in Table 3. As it can be seen, even the best third independent variable, y co-ordinate for Scots pine and temperature sum for Norway spruce and birch, was of minor significance. The models for the diameter at breast height for the entire country are presented in Table 4.

Further models for diameter at breast height were formulated after dividing the data into four geographical areas. General information on these regional models is presented in Table 5. The RMSEs of the models for the ecoregions varied

Table 4. Parameter estimates and t-test statistics (t) of models for diameter at breast height for the entire country. The first digit in number of model refers to the geographic area (Fig. 1) in question (number of the area or 9 as an indication of the entire country), the second digit the form of the model and the last digit the tree species.

No. of model	Constant Estimate	t	H Estimate	t	D_{crm} Estimate	t	D9,ts or y Estimate	t
9.1.0	–0.905	–13.92	1.176	196.00	–	–	–	–
9.1.1	–0.801	–7.63	1.204	120.40	–	–	–	–
9.1.2	–0.524	–6.39	1.145	163.57	–	–	–	–
9.1.3	–1.591	–9.94	1.153	76.87	–	–	–	–
9.2.0	–1.525	–17.33	–	–	2.334	155.60	–	–
9.2.1	–0.238	–2.27	–	–	2.183	121.28	–	–
9.2.2	–3.600	–21.30	–	–	2.719	93.76	–	–
9.2.3	–0.982	–6.25	–	–	2.019	74.78	–	–
9.3.0	–3.424	–58.03	0.806	134.33	1.148	82.00	–	–
9.3.1	–3.155	–42.64	0.730	91.25	1.323	82.69	–	–
9.3.2	–3.214	–35.71	0.861	95.67	1.016	44.17	–	–
9.3.3	–3.341	–26.31	0.700	46.67	1.143	42.33	–	–
9.4.0	–1.907	–26.49	0.733	122.17	1.066	82.00	–0.771	–33.52
9.4.1	–11.934	–22.20	0.752	91.48	1.311	84.62	0.00122	17.43
9.4.2	0,088	0.58	0.876	107.07	1.033	47.74	–0.00312	–26.00
9.4.3	–0.656	–3.59	0.805	52.08	1.056	40.64	–0.00302	–18.88

Table 5. Statistical properties of regional models. $\mathbf{R^2}$ is divided into cluster (Clus), plot (Plot) and tree (Tree) effects. Proportion of total variance (VAR%) is calculated for clusters and plots. The first digit in number of model refers to the geographic area (Fig. 1) in question (number of the area or 9 as an indication of the entire country), the second digit the form of the model and the last digit the tree species.

Model	No. of model	Predictor	RMSE %	RMSE mm	R^2 Clus	R^2 Plot	R^2 Tree	VAR% Clus	VAR% Plot	VAR
Area 1										
All	1.1.0	h	12.0	20.6	0.63	0.84	0.70	0.12	0.31	2.336
Pine	1.1.1	h	10.3	18.7	–	0.86	0.56	0	0.40	1.839
Spruce	1.1.2	h	11.2	18.5	–	0.93	0.77	0.29	0.20	1.940
Birch	1.1.3	h	12.5	18.8	–	0.86	0.76	0	0.82	2.140
All	1.2.0	d_{crm}	13.7	23.4	0.79	0.70	0.67	0.05	0.45	3.018
Pine	1.2.1	d_{crm}	12.8	23.2	–	0.68	0.56	0	0.61	2.844
Spruce	1.2.2	d_{crm}	12.5	20.6	–	0.82	0.66	0	0.40	2.418
Birch	1.2.3	d_{crm}	15.1	22.7	–	0.79	0.61	–	0.80	3.144
All	1.3.0	h, d_{crm}	8.7	15.0	0.81	0.90	0.86	0.11	0.37	1.237
Pine	1.3.1	h, d_{crm}	7.6	13.8	–	0.93	0.75	0	0.39	1.011
Spruce	1.3.2	h, d_{crm}	7.2	11.9	–	0.96	0.90	0.19	0.25	0.801
Birch	1.3.3	h, d_{crm}	8.6	12.9	–	0.96	0.67	0	0.48	1.019
Pine	1.4.1	h, d_{crm}, age_m	7.1	12.9	–	0.95	0.75	0	0.29	0.875
Spruce	1.4.2	h, d_{crm}, ba	6.7	11.1	–	0.97	0.90	0.14	0.22	0.702
Birch	1.4.3	h, d_{crm}, $d_{1,3m}$	8.5	12.7	–	0.95	0.76	0	0.61	0.986

Table 5. continued

Model	No. of model	Predictor	RMSE %	RMSE mm	R^2 Clus	R^2 Plot	R^2 Tree	VAR% Clus	VAR% Plot	VAR
Area 2										
All	2.1.0	h	11.6	17.4	0.40	0.88	0.79	0.07	0.30	1.888
Pine	2.1.1	h	11.6	18.1	0.82	0.89	0.64	0.09	0.31	1.986
Spruce	2.1.2	h	9.6	14.8	0.66	0.95	0.86	0.17	0.24	1.316
Birch	2.1.3	h	10.7	13.8	–	0.85	0.78	0	0.46	1.390
All	2.2.0	d_{crm}	14.9	22.3	–0.09	0.81	0.65	0.08	0.29	3.091
Pine	2.2.1	d_{crm}	13.3	20.8	0.59	0.78	0.71	0.16	0.47	2.597
Spruce	2.2.2	d_{crm}	14.7	22.6	0.53	0.87	0.67	0.10	0.28	3.071
Birch	2.2.3	d_{crm}	12.5	16.1	–	0.91	0.63	0.14	0.21	1.890
All	2.3.0	h, d_{crm}	9.1	13.6	0.71	0.93	0.87	0.06	0.31	1.153
Pine	2.3.1	h, d_{crm}	7.4	11.6	0.89	0.97	0.84	0.13	0.20	0.811
Spruce	2.3.2	h, d_{crm}	7.2	11.1	0.88	0.97	0.92	0.11	0.24	0.742
Birch	2.3.3	h, d_{crm}	8.0	10.3	–	0.94	0.86	0.06	0.35	0.780
Pine	2.4.1	h, d_{crm}, D9	7.4	11.5	0.89	0.97	0.84	0.14	0.21	0.801
Spruce	2.4.2	h, d_{crm}, D9	7.0	11.1	0.88	0.98	0.92	0.11	0.22	0.694
Birch	2.4.3	h, d_{crm}, D9	7.5	9.6	–	0.95	0.88	0.10	0.32	0.681
Area 3										
All	3.1.0	h	12.2	15.6	0.64	0.80	0.77	0.13	0.24	1.796
Pine	3.1.1	h	12.0	16.2	0.71	0.85	0.72	0.17	0.25	1.833
Spruce	3.1.2	h	8.9	12.1	0.61	0.97	0.87	0.23	0.11	1.008
Birch	3.1.3	h	12.4	12.9	0.44	0.78	0.72	0.26	0.22	1.524
All	3.2.0	d_{crm}	14.6	18.6	0.74	0.75	0.63	0.07	0.21	2.548
Pine	3.2.1	d_{crm}	12.8	17.3	0.73	0.74	0.74	0.13	0.39	2.088
Spruce	3.2.2	d_{crm}	15.2	20.5	0.76	0.74	0.62	0.05	0.28	2.911
Birch	3.2.3	d_{crm}	12.2	12.7	0.85	0.82	0.60	0.07	0.18	1.485
All	3.3.0	h, d_{crm}	9.5	12.1	0.77	0.90	0.86	0.14	0.21	1.078
Pine	3.3.1	h, d_{crm}	7.5	10.2	0.88	0.96	0.87	0.17	0.17	0.723
Spruce	3.3.2	h, d_{crm}	7.7	10.4	0.63	0.97	0.92	0.31	0.13	0.741
Birch	3.3.3	h, d_{crm}	8.9	9.3	0.79	0.91	0.82	0.19	0.17	0.787
Pine	3.4.1	h, d_{crm}, D9	7.3	9.9	0.90	0.96	0.88	0.14	0.20	0.684
Spruce	3.4.2	h, d_{crm}, ts	7.0	9.4	0.87	0.96	0.92	0.13	0.19	0.611
Birch	3.4.3	h, d_{crm}, D9	8.1	8.4	0.91	0.91	0.84	0.10	0.21	0.648
Area 4										
All	4.1.0	h	12.3	17.4	–	0.82	0.75	0.18	0.14	2.036
Pine	4.1.1	h	12.7	18.7	0.44	0.77	0.70	0.21	0.21	2.267
Spruce	4.1.2	h	9.4	13.9	0.81	0.82	0.82	0.11	0.27	1.247
Birch	4.1.3	h	13.2	15.0	–	0.75	0.67	0.13	0.33	1.893
All	4.2.0	d_{crm}	14.0	19.8	–	0.75	0.64	0.12	0.14	2.642
Pine	4.2.1	d_{crm}	11.9	17.4	0.42	0.92	0.70	0.25	0.08	1.966
Spruce	4.2.2	d_{crm}	14.5	21.4	–0.13	1.00	0.50	0.27	0	2.966
Birch	4.2.3	d_{crm}	13.8	15.7	–	0.93	0.50	0.17	0.09	2.061
All	4.3.0	h, d_{crm}	9.4	13.3	–	0.95	0.85	0.26	0.06	1.198
Pine	4.3.1	h, d_{crm}	8.7	12.7	0.58	0.99	0.85	0.34	0.02	1.050
Spruce	4.3.2	h, d_{crm}	7.8	11.5	1.00	0.84	0.87	0	0.36	0.858
Birch	4.3.3	h, d_{crm}	10.5	11.9	–	0.89	0.78	0.17	0.24	1.185
Pine	4.4.1	h, d_{crm}, age_m	8.3	12.2	0.70	0.99	0.84	0.27	0.03	0.964
Spruce	4.4.2	h, d_{crm}, ba	7.0	10.4	1.00	0.97	0.85	0	0.09	0.699
Birch	4.4.3	h, d_{crm}, D9	9.9	11.2	–	0.96	0.79	0.27	0.10	1.052

Table 6. Parameter estimates and t-test statistics (t) of regional models for diameter at breast height. The first digit in number of model refers to the geographic area (Fig. 1) in question (number of the area or 9 as an indication of the entire country), the second digit the form of the model and the last digit the tree species.

No. of model	Constant Estimate	Constant t	H Estimate	H t	D_{crm} Estimate	D_{crm} t	Age, ba, $d_{1,3m}$, D9 or ts Estimate	Age, ba, $d_{1,3m}$, D9 or ts t
1.1.0	–2.145	–3.85	1.291	28.07	–	–	–	–
1.1.1	–1.775	–2.10	1.314	18.25	–	–	–	–
1.1.2	–1.740	–2.36	1.228	20.13	–	–	–	–
1.1.3	–5.533	–4.03	1.475	13.53	–	–	–	–
1.2.0	–0.805	–1.36	–		2.327	24.24	–	–
1.2.1	2.628	3.34	–		1.796	14.37	–	–
1.2.2	–3.444	–3.52	–		2.774	16.81	–	–
1.2.3	–1.867	–1.30	–		2.549	11.18	–	–
1.3.0	–4.765	–11.03	0.846	19.67	1.321	16.31	–	–
1.3.1	–3.324	–5.15	0.910	13.79	1.029	10.19	–	–
1.3.2	–5.512	–9.57	0.800	14.81	1.512	11.91	–	–
1.3.3	–6.978	–6.87	0.972	7.65	1.271	5.23	–	–
2.1.0	–1.049	–11.16	1.159	144.86	–	–	–	–
2.1.1	–0.785	–4.49	1.177	78.47	–	–	–	–
2.1.2	–0.960	–8.65	1.168	129.78	–	–	–	–
2.1.3	–2.938	–12.50	1.226	61.30	–	–	–	–
2.2.0	–2.387	–16.81	–		2.474	103.08	–	–
2.2.1	–0.444	–2.36	–		2.226	69.56	–	–
2.2.2	–4.088	–17.93	–		2.769	74.84	–	–
2.2.3	–1.492	–5.72	–		2.106	48.98	–	–
2.3.0	–3.733	–42.42	0.807	89.67	1.144	54.48	–	–
2.3.1	–3.524	–28.42	0.729	56.08	1.345	49.81	–	–
2.3.2	–3.835	–33.94	0.860	78.18	1.079	38.54	–	–
2.3.3	–4.250	–23.10	0.804	36.55	1.028	25.70	–	–
3.1.0	–1.187	–12.24	1.212	134.67	–	–	–	–
3.1.1	–0.948	–6.72	1.218	87.00	–	–	–	–
3.1.2	–0.457	–3.63	1.161	96.75	–	–	–	–
3.1.3	–1.984	–8.74	1.206	52.43	–	–	–	–
3.2.0	–1.193	–9.32	–		2.260	98.26	–	–
3.2.1	–0.547	–3.80	–		2.221	85.42	–	–
3.2.2	–2.841	–9.63	–		2.594	48.94	–	–
3.2.3	–0.363	1.76	–		1.896	51.24	–	–
3.3.0	–3.501	–40.71	0.838	83.80	1.125	56.25	–	–
3.3.1	–3.306	–34.08	0.743	67.55	1.334	60.64	–	–
3.3.2	–2.739	–19.02	0.920	61.33	0.868	22.84	–	–
3.3.3	–3.420	–19.66	0.741	33.68	1.107	31.63	–	–
4.1.0	–1.717	–6.66	1.378	53.00	–	–	–	–
4.1.1	–1.854	–5.21	1.389	39.69	–	–	–	–
4.1.2	–0.343	–0.77	1.275	28.33	–	–	–	–
4.1.3	–1.480	–2.31	1.327	18.96	–	–	–	–
4.2.0	0.690	2.60	–		1.999	42.53	–	–
4.2.1	1.177	4.51	–		1.957	42.54	–	–
4.2.2	–1.005	–1.17	–		2.422	15.23	–	–
4.2.3	–0.721	–1.08	–		1.982	17.09	–	–
4.3.0	–3.432	16.74	0.941	37.64	1.087	27.87	–	–
4.3.1	–2.734	–11.34	0.797	25.71	1.230	28.60	–	–
4.3.2	–2.948	–6.25	1.013	21.55	0.962	8.83	–	–
4.3.3	–3.770	–6.77	0.886	12.48	1.108	10.17	–	–
1.4.1	–3.913	–6.30	0.890	14.59	0.985	10.26	0.016	4.00
1.4.2	–4.201	–6.28	0.802	15.73	1.490	12.31	–0.047	–3.13
1.4.3	–6.863	–6.88	0.965	7.72	1.051	4.29	0.058	2.15
2.4.1	–2.978	–19.72	0.721	55.46	1.279	45.68	–0.379	–6.32
2.4.2	–2.836	–19.97	0.803	73.00	1.059	39.22	–0.493	–10.96
2.4.3	–2.859	–13.55	0.731	33.23	0.981	25.82	–0.738	–11.35
3.4.1	–2.311	–18.79	0.712	64.73	1.233	56.05	–0.538	–12.81
3.4.2	1.469	4.33	0.934	66.71	0.888	24.67	–0.00430	–13.44
3.4.3	–1.688	–8.75	0.666	33.33	0.996	30.18	–0.789	–14.89
4.4.1	–2.728	–11.56	0.751	23.47	1.234	28.70	0.005	5.00
4.4.2	–2.287	–5.02	1.042	23.16	0.949	9.40	–0.053	–5.30
4.4.3	–2.141	–3.37	0.745	10.21	1.134	11.01	–0.806	–4.63

between 8.4 and 23.4 mm depending on the combination of independent variables and species. Negative R^2-values in the table indicate that estimated variances may not change logically, e.g. because of correlated regressors.

The third variable for Scots pine in area 1 was the mean age of the growing stock (in years), for Norway spruce the basal area (m^2/ha) and for birch the mean diameter (cm). In area 2, the third variable for all tree species was relative tree height class (D9). The third variable for Norway spruce in area 3 was the temperature sum (°) and for Scots pine and birch the relative tree height class (D9), while in area 4 it was for Scots pine the relative tree height class (D9), for Norway spruce the basal area (m^2/ha) and for birch the mean age of the growing stock (in years). The regional models for diameter at breast height are presented in Table 6.

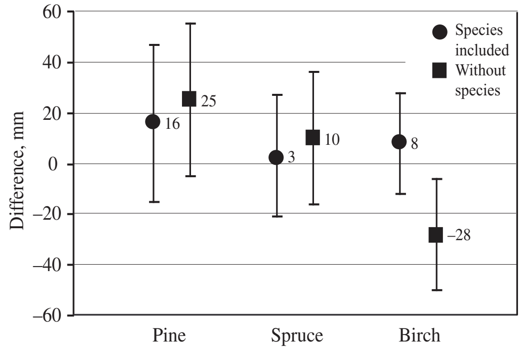

Fig. 3. Averages and standard deviations for predicted values of $d_{1,3} = f(h, d_{crm})$ in models for area 2 with and without information on tree species.

4.3 Validation of the Models for Diameter at Breast Height

The functionality of the models was tested with data collected from a site near the Hyytiälä Research Station (in area 2). One aim was to evaluate the convenience of the division into regions, i.e. to determine whether the predicted values differed between the models for the areas and between the models for area 2 and those for the entire country. This implies that the models for area 2 were compared in terms of functionality with those for the other areas, taking into account the differences between tree species.

The test results by tree species are presented in Table 7. When evaluating these results, it should be noted that the test data for all models are the same.

The average diameter at breast height for all three tree species is overestimated when the height of the tree is the only independent variable, whereas the models with maximum crown diameter as the independent variable always underestimate the diameter at breast height. When both variables (h, d_{crm}) are included, the prediction is virtually unbiased.

The average standard deviation when maximum crown width alone was the independent variable was 4.9 cm (about 22% from mean dbh), being smallest for birch. When tree height was the only independent variable, the standard deviation was 3.2 cm, which is about 14% from the mean dbh (smallest for Norway spruce), and when both variables (h, d_{crm}) were included, it was 2.7 cm (about 12% from mean dbh). The standard deviation for the latter model was equally small for birch and Norway spruce if evaluated in a relative unit of measure, and largest for Scots pine. The third variable models were also tested. In all cases, the effect of the third variable was minor.

The models for the entire country based on the test data predict the diameter at breast height equally well. Only a slight difference existed between the predictions given by the models for the entire country and for area 2, but it is noteworthy that 85% of the trees in the data set for the entire country were located in areas 2 and 3. Had the test data been taken from area 1 or area 4, the differences would undoubtedly have been more marked.

The influence of tree species was studied by comparing models formulated for all tree species with species-specific models. This was done again with the test data from area 2. As might be expected, the latter models predicted the diameter at breast height better than the former, the differences being small for the conifers but considerable for birch (Fig. 3).

The need for ecoregions was tested using the combined model in which the observations from all regions were included. Because the results of F-tests revealed that differences existed among

Table 7. Test statistics of the models for dbh using external data from the Hyytiälä Research Station. Bias refers to the mean of differences between observed and predicted diameters in absolute terms (mm) and proportional terms (%) per cent from mean diameter. S.E. refers to the standard deviation for the differences.

	n	f(h)		f(d_{crm})		f(h, d_{crm})	
		Bias mm (%)	S.E. mm (%)	Bias mm (%)	S.E. mm (%)	Bias mm (%)	S.E. mm (%)
Scots pine							
Entire coutry	346	–26(11)	36(15)	66(28)	51(22)	9(4)	31(13)
Area 1	346	–45(19)	37(16)	52(22)	51(22)	–10(4)	27(12)
Area 2	346	–15(6)	34(15)	65(28)	52(22)	16(7)	31(13)
Area 3	346	–28(12)	36(15)	70(30)	51(22)	6(3)	30(13)
Area 4	346	–79(34)	35(15)	65(28)	51(22)	–16(7)	29(12)
Norway spruce							
Entire coutry	245	–17(8)	30(13)	48(22)	48(22)	–4(2)	24(11)
Area 1	245	–16(7)	30(13)	35(16)	48(22)	–1(0)	24(11)
Area 2	245	–14(6)	30(13)	52(23)	48(22)	3(1)	24(11)
Area 3	245	–26(12)	30(13)	48(22)	49(22)	–16(7)	24(11)
Area 4	245	–83(37)	32(14)	28(13)	49(22)	–70(31)	25(11)
Birch							
Entire coutry	120	–29(15)	32(17)	55(29)	32(17)	4(2)	21(11)
Area 1	120	–48(25)	33(18)	14(7)	42(22)	–24(13)	24(13)
Area 2	120	–19(10)	32(17)	54(29)	33(18)	8(4)	20(11)
Area 3	120	–39(21)	32(17)	59(31)	31(16)	–4(2)	21(11)
Area 4	120	–111(59)	34(18)	54(29)	32(17)	–54(29)	23(12)
All tree species							
Entire coutry	711	–22(10)	32(14)	59(27)	49(22)	1(0)	27(12)
Area 1	711	–34(15)	32(14)	41(18)	50(22)	–7(3)	26(12)
Area 2	711	–10(4)	33(15)	60(27)	49(22)	11(5)	27(12)
Area 3	711	–29(13)	32(14)	62(28)	49(22)	–5(2)	26(12)
Area 4	711	–89(40)	35(16)	55(25)	49(22)	–45(20)	25(11)

the models from different geographical areas, the differences between pairs of ecoregions were tested. Results of these tests for model $d_{1,3}$ = f(h, d_{crm}) by tree species are presented in Table 8. The differences between the areas were mostly statistically significant for the models $d_{1,3}$ = f(h), $d_{1,3}$ = f(d_{crm}) and $d_{1,3}$ = f(h, d_{crm}). Only a few combinations of model form and tree species formed exceptions on some pairs of areas. Only minor differences were present between the trees species. The main features of the phenomenon are easily perceived by examining the means of the prediction errors in Table 7. The tests indicate that the division into areas is helpful and can be recommended for use in the context of the models formulated here for diameter at breast height.

The need for regional models can also be seen in Fig. 4, where the residuals (+/–) of the diameter models are presented as interpolated surfaces, using the inverse distance weighted (IDW) method. The residuals of the model for the entire country were quite large and unevenly distributed for all tree species. For example, for Scots pine, the model underestimated the diameter on average in northern Finland but overestimated it in southern Finland. With the regional models, the residuals were lower and distributed more evenly over the whole country. It should be noted that the residual surfaces in the most northern part of country could be misleading because of interpolation problems arising from the small number of observations.

Table 8. F-tests of the regional differences of diameter models: d=f(h, d_{crm}) by tree species.

Ecoregion pair	Full model df_F	SSE_F	MSE_F	Reduced model df_R	SSE_R	MSE_R	n	F-value
Pine								
Combined	5291	4253.44	0.803901	5300	4599.43	0.867817	5303	47.821*
Area1–Area2	1963	1629.158	0.829933	1966	1647.284	0.837886	1969	7.280*
Area1–Area3	2764	2050.791	0.741965	2767	2054.066	0.742344	2770	1.471
Area1–Area4	816	853.907	1.046455	819	885.990	1.081795	822	10.220*
Area2–Area3	4475	3395.12	0.758686	4478	3478.022	0.776691	4481	36.424*
Area2–Area4	2527	2203.445	0.871961	2530	2534.028	1.001592	2533	126.375*
Area3–Area4	3328	2628.285	0.789749	3331	2794.609	0.83897	3334	70.201*
Spruce								
Combined	3649	2766.84	0.758246	3658	3456.967	0.945043	3661	101.129*
Area1–Area2	2278	1674.423	0.735041	2281	1681.149	0.737023	2284	3.050*
Area1–Area3	1298	990.151	0.762828	1301	1009.256	0.775754	1304	8.348*
Area1–Area4	275	240.846	0.875803	278	411.107	1.478802	281	64.802*
Area2–Area3	3374	2508.124	0.743368	3377	2773.908	0.821412	3380	119.180*
Area2–Area4	2351	1751.189	0.74487	2354	2306.113	0.979657	2357	248.331*
Area3–Area4	1371	1048.793	0.764984	1374	1264.257	0.920129	1377	93.886*
Birch								
Combined	2270	1896.433	0.835433	2279	2275.035	0.99826	2282	50.353*
Area1–Area2	904	738.016	0.816389	907	760.215	0.838164	910	9.064*
Area1–Area3	1223	996.492	0.814793	1226	1000.365	0.815958	1229	1.584
Area1–Area4	215	252.360	1.173769	218	287.676	1.319613	221	10.029*
Area2–Area3	2055	1614.348	0.785571	2058	1763.908	0.857098	2061	63.461*
Area2–Area4	1047	893.412	0.853307	1050	1205.01	1.147629	1053	121.722*
Area3–Area4	1366	1155.881	0.846179	1369	1286.066	0.93942	1372	51.284*

* Significant F-value.

4.4 Models for Tree Age

The models for the age of the tree were formulated with the same procedure as diameter models, using height of the tree or maximum crown width or both as independent variables. General information on the age models for entire country is presented in Table 9, and the models are listed in Table 10.

Further age models were formulated for four ecoregions. General information on these regional models are presented in Table 11. The RMSEs of the models for the ecoregions varied between 2.8 and 9.7 years depending on the combination of independent variables and species. Negative R^2-values in the table indicate that estimated variances may not change logically, e.g. because of correlated regressors. The regional age models are presented in Table 12.

For the all species, the age of the tree was dependent most on its height, and inclusion of the maximum crown diameter increased the coefficient of determination only slightly. For birch, however, the maximum crown diameter was more important independent variable, than for conifers. In some combinations of regions and tree species maximum crown diameter was not statistically significant as independent variable in f(h, d_{crm}) models. However, the coefficient of determination was quite low in all cases.

4.5 Validation of the Models for Tree Age

A validation data set from a site near the Hyytiälä Research Station was also used to evaluate the models and ensure reliability in the prediction for tree age. The growing stock of the site was quite homogenous and only some age measurements were done. So, mean age of the stratifications were used as tree age. This should be noted when evaluating the test results.

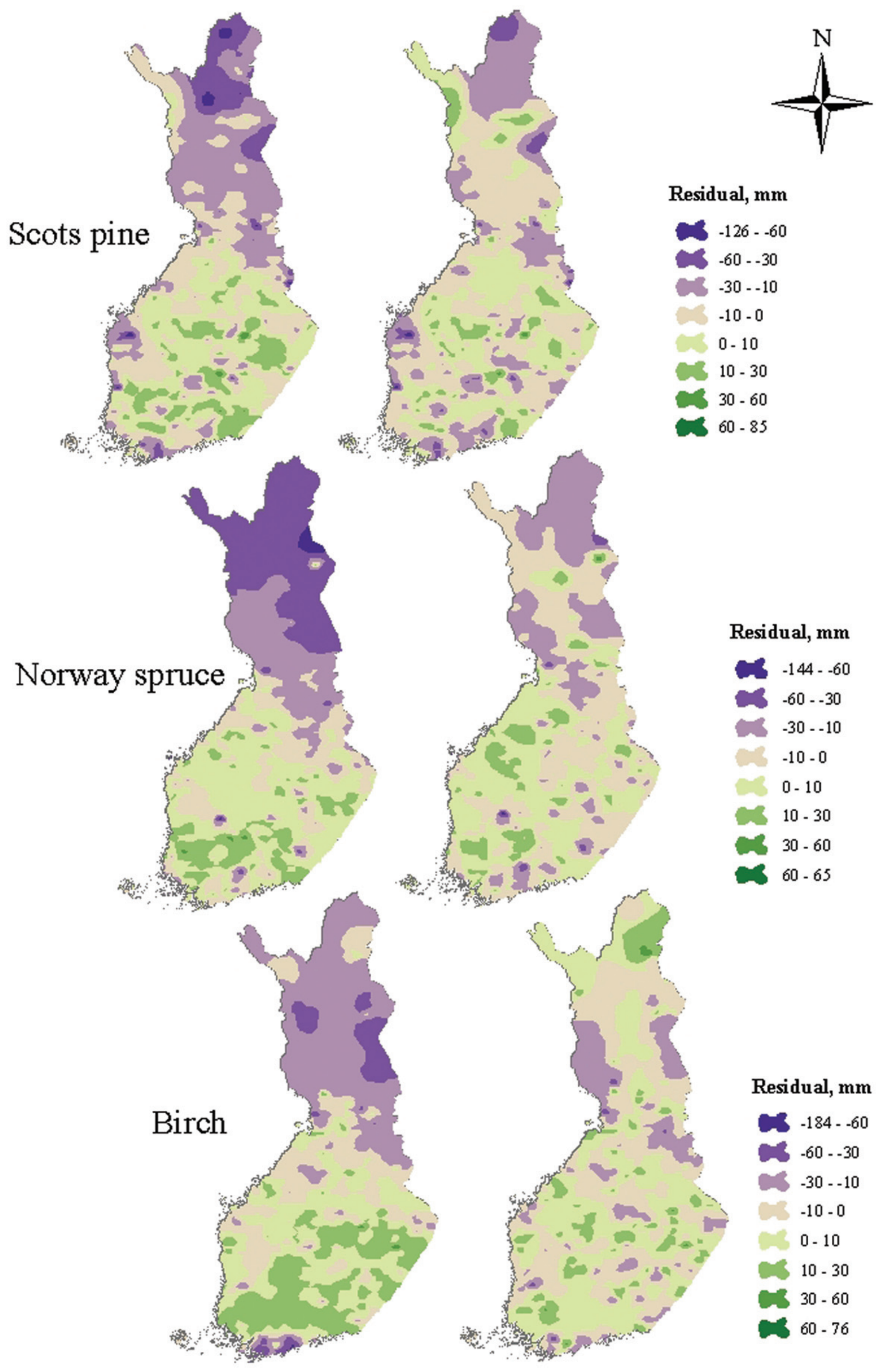

Fig. 4. Interpolated residual surfaces obtained from the dbh models for Scots pine, Norway spruce and birch formulated over the entire country (left side) and for the four geographical areas (right side).

Table 9. Statistical properties of the age models for the entire country. $\mathbf{R^2}$ is divided into cluster (Clus), plot (Plot) and tree (Tree) effects. Proportion of total variance (VAR%) is calculated for clusters and plots. The first digit in number of model refers to the geographic area (Fig. 1) in question (number of the area or 9 as an indication of the entire country), the second digit the form of the model and the last digit the tree species.

Model	No. of model	Predictor	RMSE		R^2			VAR%		VAR
			%	Years	Clus	Plot	Tree	Clus	Plot	
All	9.5.0	h	10.8	6.4	–0.29	0.42	0.42	0.32	0.51	0.181
Pine	9.5.1	h	11.0	6.5	0.11	0.45	0.41	0.39	0.52	0.189
Spruce	9.5.2	h	9.2	6.1	–	0.55	0.55	0.41	0.47	0.142
Birch	9.5.3	h	10.4	5.0	–0.19	0.42	0.41	0.55	0.32	0.155
All	9.6.0	d_{crm}	11.8	7.0	–0.13	0.20	0.25	0.24	0.58	0.217
Pine	9.6.1	d_{crm}	12.8	7.5	0.04	0.15	0.31	0.31	0.61	0.252
Spruce	9.6.2	d_{crm}	10.2	6.7	–0.83	0.31	0.32	0.25	0.60	0.173
Birch	9.6.3	d_{crm}	10.1	4.8	0.06	0.36	0.29	0.47	0.37	0.146
All	9.7.0	h, d_{crm}	10.8	6.4	–0.29	0.41	0.42	0.32	0.51	0.182
Pine	9.7.1	h, d_{crm}	11.1	6.6	0.10	0.44	0.41	0.39	0.53	0.192
Spruce	9.7.2	h, d_{crm}	9.3	6.1	–	0.54	0.55	0.41	0.48	0.143
Birch	9.7.3	h, d_{crm}	10.0	4.8	–0.08	0.44	0.44	0.54	0.33	0.144

Table 10. Parameter estimates and t-test statistics (t) of the age models for the entire country. The first digit in number of model refers to the geographic area (Fig. 1) in question (number of the area or 9 as an indication of the entire country), the second digit the form of the model and the last digit the tree species.

No. of model	Constant		H		D_{crm}	
	Esimate	t	Estimate	t	Estimate	t
9.5.0	1.684	58.07	0.490	81.67	–	–
9.5.1	1.376	30.58	0.556	61.78	–	–
9.5.2	2.085	56.35	0.429	53.63	–	–
9.5.3	1.252	15.46	0.544	32.00	–	–
9.6.0	2.540	94.07	–	–	0.420	52.50
9.6.1	2.840	94.67	–	–	0.332	36.89
9.6.2	2.459	52.32	–	–	0.474	36.46
9.6.3	2.225	39.73	–	–	0.454	28.38
9.7.0	1.639	56.52	0.436	54.50	0.087	9.67
9.7.1	1.407	31.27	0.520	40.00	0.040	3.64
9.7.2	2.019	49.24	0.398	36.18	0.061	3.81
9.7.3	1.264	16.00	0.371	16.86	0.232	12.21

The functionality of the models was different depending on the combination of independent variables and species. For conifers, the prediction of tree age was almost equal when using models, f(h) or f(h, d_{crm}). Maximum crown diameter as the independent variable seems not to be suitable independent variable of its own. However, maximum crown diameter as the independent variable was the best age model for birch. For Scots pine, it seems that the models for ecoregion 3 were the best although the test site is in area 2. It seems that only height or both height and maximum crown diameter as independent variables for conifers can be used. Maximum crown diameter as the only independent variable worked well for birch. The test results by tree species are presented in Table 13. When evaluating these results, it should be noted that the test data for all models are the same.

The average standard deviation of age when maximum crown width alone was the independent variable was about 30 years (41% from mean age). When tree height was the only independent variable or both variables (h, d_{crm}) were included, the standard deviation was about 27 years (37% from mean age). For all models, the standard

Table 11. Statistical properties of regional age models. $\mathbf{R^2}$ is divided into cluster (Clus), plot (Plot) and tree (Tree) effects. Proportion of total variance (VAR%) is calculated for clusters and plots. The first digit in number of model refers to the geographic area (Fig. 1) in question (number of the area or 9 as an indication of the entire country), the second digit the form of the model and the last digit the tree species.

Model	No. of model	Predictor	RMSE %	RMSE Years	R^2 Clus	R^2 Plot	R^2 Tree	VAR% Clus	VAR% Plot	VAR
Area 1										
All	1.5.0	h	8.0	4.6	–	0.32	0.38	0	0.82	0.100
Pine	1.5.1	h	7.8	4.8	–	0.21	0.41	0	0.94	0.100
Spruce	1.5.2	h	7.9	4.5	–	0.36	0.46	0	0.88	0.098
Birch	1.5.3	h	6.2	2.8	–	0.66	0.49	0	0.94	0.053
All	1.6.0	d_{crm}	8.6	4.9	–	0.22	0.24	0	0.81	0.116
Pine	1.6.1	d_{crm}	8.3	5.1	–	0.10	0.26	0	0.94	0.114
Spruce	1.6.2	d_{crm}	8.3	4.7	–	0.32	0.26	0	0.85	0.108
Birch	1.6.3	d_{crm}	8.1	3.6	–	0.40	0.50	0	0.96	0.091
All	1.7.0	h, d_{crm}	7.9	4.5	–	0.33	0.41	0	0.83	0.098
Pine	1.7.1	h, d_{crm}	7.8	4.8	–	0.21	0.45	0	0.95	0.099
Spruce	1.7.2	h, d_{crm}	7.7	4.4	–	0.40	0.47	0	0.87	0.093
Birch	1.7.3	h, d_{crm}	6.1	2.8	–	0.67	0.48	0	0.93	0.052
Area 2										
All	2.5.0	h	9.7	5.1	–	0.49	0.42	0.12	0.71	0.139
Pine	2.5.1	h	10.7	5.4	0.34	0.51	0.30	0.15	0.78	0.163
Spruce	2.5.2	h	7.3	4.3	–	0.54	0.53	0	0.82	0.085
Birch	2.5.3	h	9.4	4.2	–	0.57	0.39	0.29	0.59	0.121
All	2.6.0	d_{crm}	11.1	5.9	–0.63	0.28	0.26	0.07	0.76	0.184
Pine	2.6.1	d_{crm}	13.6	6.9	0.10	0.15	0.25	0.13	0.83	0.264
Spruce	2.6.2	d_{crm}	8.6	5.0	–	0.35	0.36	0	0.82	0.118
Birch	2.6.3	d_{crm}	10.0	4.5	–	0.48	0.26	0.24	0.63	0.138
All	2.7.0	h, d_{crm}	9.7	5.1	–0.88	0.49	0.42	0.11	0.71	0.139
Pine	2.7.1	h, d_{crm}	10.7	5.4	0.35	0.51	0.30	0.15	0.78	0.162
Spruce	2.7.2	h, d_{crm}	7.3	4.3	–	0.53	0.55	0	0.82	0.085
Birch	2.7.3	h, d_{crm}	9.2	4.1	–	0.60	0.42	0.31	0.57	0.117
Area 3										
All	3.5.0	h	10.3	6.2	0.20	0.33	0.41	0.24	0.55	0.167
Pine	3.5.1	h	9.8	5.9	0.41	0.40	0.44	0.28	0.60	0.152
Spruce	3.5.2	h	8.7	6.5	–0.73	0.51	0.58	0.36	0.48	0.133
Birch	3.5.3	h	9.2	4.4	0.18	0.24	0.42	0.50	0.31	0.121
All	3.6.0	d_{crm}	11.5	7.0	0.04	0.14	0.25	0.23	0.56	0.211
Pine	3.6.1	d_{crm}	11.8	7.1	0.09	0.14	0.32	0.30	0.60	0.220
Spruce	3.6.2	d_{crm}	10.0	7.4	–0.47	0.20	0.38	0.24	0.59	0.175
Birch	3.6.3	d_{crm}	9.4	4.5	0.20	0.19	0.29	0.47	0.32	0.127
All	3.7.0	h, d_{crm}	10.3	6.2	0.20	0.33	0.42	0.24	0.56	0.167
Pine	3.7.1	h, d_{crm}	9.9	5.9	0.41	0.40	0.44	0.28	0.60	0.153
Spruce	3.7.2	h, d_{crm}	8.7	6.5	–0.74	0.50	0.59	0.36	0.49	0.135
Birch	3.7.3	h, d_{crm}	9.0	4.3	0.24	0.25	0.45	0.49	0.32	0.116
Area 4										
All	4.5.0	h	9.5	7.8	0.05	0.44	0.50	0.55	0.21	0.165
Pine	4.5.1	h	9.1	7.2	0.29	0.49	0.51	0.61	0.24	0.150
Spruce	4.5.2	h	8.1	8.8	0.03	0.01	0.64	0.55	0.30	0.138
Birch	4.5.3	h	8.3	5.6	0.05	0.31	0.53	0.50	0.31	0.118
All	4.6.0	d_{crm}	10.4	8.5	0.02	0.21	0.29	0.47	0.24	0.199
Pine	4.6.1	d_{crm}	10.3	8.2	0.11	0.32	0.36	0.59	0.25	0.192
Spruce	4.6.2	d_{crm}	8.9	9.7	0.09	–0.31	0.27	0.42	0.32	0.168
Birch	4.6.3	d_{crm}	8.2	5.5	0.02	0.65	0.27	0.52	0.16	0.115
All	4.7.0	h, d_{crm}	9.4	7.7	0.05	0.44	0.51	0.55	0.21	0.164
Pine	4.7.1	h, d_{crm}	9.1	7.2	0.27	0.51	0.54	0.62	0.24	0.150
Spruce	4.7.2	h, d_{crm}	8.1	8.8	0.05	–0.04	0.64	0.54	0.31	0.139
Birch	4.7.3	h, d_{crm}	8.0	5.3	0.07	0.47	0.55	0.53	0.26	0.108

Table 12. Parameter estimates and t-test statistics (t) of regional age models. The first digit in number of model refers to the geographic area (Fig. 1) in question (number of the area or 9 as an indication of the entire country), the second digit the form of the model and the last digit the tree species.

No. of	Constant		H		D_{crm}	
model	Estimate	t	Estimate	t	Estimate	t
1.5.0	1.616	8.16	0.490	12.25	–	–
1.5.1	2.075	7.83	0.416	7.70	–	–
1.5.2	1.884	7.54	0.430	8.43	–	–
1.5.3	0.752	1.91	0.615	7.88	–	–
1.6.0	2.693	18.83	–	–	0.374	9.35
1.6.1	3.393	24.41	–	–	0.200	5.41
1.6.2	2.326	9.12	–	–	0.475	6.60
1.6.3	2.655	12.01	–	–	0.329	11.10
1.7.0	1.599	8.24	0.385	7.70	0.151	3.28
1.7.1	2.150	8.24	0.346	5.41	0.075	1.89
1.7.2	1.705	6.61	0.338	5.12	0.180	2.17
1.7.3	0.788	1.78	0.590	4.28	0.025	0.25
2.5.0	1.644	43.26	0.466	58.25	–	–
2.5.1	1.306	18.45	0.525	36.01	–	–
2.5.2	2.113	54.18	0.394	49.94	–	–
2.5.3	0.858	7.27	0.592	24.67	–	–
2.6.0	2.365	62.24	–	–	0.432	39.27
2.6.1	2.902	63.09	–	–	0.263	21.21
2.6.2	2.380	49.58	–	–	0.457	35.15
2.6.3	2.064	24.10	–	–	0.468	19.67
2.7.0	1.599	41.00	0.424	38.55	0.070	5.38
2.7.1	1.282	17.81	0.544	27.20	–0.020	–1.25
2.7.2	1.994	47.48	0.335	29.72	0.115	7.24
2.7.3	0.896	7.74	0.452	13.70	0.180	6.06
3.5.0	1.557	33.85	0.534	53.40	–	–
3.5.1	1.306	21.06	0.586	44.09	–	–
3.5.2	2.072	31.39	0.467	32.79	–	–
3.5.3	0.991	8.47	0.613	23.98	–	–
3.6.0	2.592	63.22	–	–	0.421	35.08
3.6.1	2.806	64.14	–	–	0.356	28.71
3.6.2	2.476	29.13	–	–	0.513	20.55
3.6.3	2.284	29.71	–	–	0.446	19.80
3.7.0	1.531	33.28	0.491	37.77	0.066	4.71
3.7.1	1.319	21.13	0.569	30.06	0.019	1.19
3.7.2	2.015	27.26	0.441	21.73	0.053	1.77
3.7.3	1.016	8.90	0.455	14.22	0.207	7.89
4.5.0	1.157	10.15	0.697	27.88	–	–
4.5.1	1.206	9.52	0.671	24.49	–	–
4.5.2	2.154	10.58	0.546	12.26	–	–
4.5.3	1.166	4.32	0.678	11.07	–	–
4.6.0	2.707	30.08	–	–	0.474	18.23
4.6.1	2.870	34.22	–	–	0.415	17.44
4.6.2	3.064	10.80	–	–	0.463	5.49
4.6.3	2.165	9.76	–	–	0.572	8.97
4.7.0	1.140	10.18	0.606	18.94	0.127	4.54
4.7.1	1.303	10.42	0.554	15.39	0.130	4.81
4.7.2	2.095	8.83	0.530	9.71	0.038	0.48
4.7.3	1.014	3.82	0.508	6.81	0.260	3.77

Table 13. Testing of the models for tree age using external data from the Hyytiälä Research Station. Bias refers to the mean of differences between observed and predicted ages in absolute terms (years) and proportional terms (%) per cent from mean age. S.E. refers to the standard deviation for the differences.

	n	f(h)		$f(d_{crm})$		$f(h, d_{crm})$	
		Bias years (%)	S.E. years (%)	Bias years (%)	S.E. years (%)	Bias years (%)	S.E. years (%)
Scots pine							
Entire coutry	346	3(4)	29(34)	21(25)	35(41)	4(5)	29(34)
Area 1	346	11(13)	31(37)	20(24)	35(41)	11(13)	32(38)
Area 2	346	21(25)	31(37)	32(38)	35(41)	20(24)	30(36)
Area 3	346	–3(4)	28(33)	19(23)	35(41)	–2(2)	28(33)
Area 4	346	–40(47)	24(28)	–1(1)	35(41)	–33(39)	26(31)
Norway spruce							
Entire coutry	245	–9(12)	25(34)	3(4)	26(36)	–5(7)	25(34)
Area 1	245	7(10)	25(34)	13(18)	27(37)	8(11)	25(34)
Area 2	245	5(7)	26(36)	14(19)	27(37)	6(8)	25(34)
Area 3	245	–25(34)	24(33)	–10(14)	26(36)	–25(34)	23(31)
Area 4	245	–89(122)	23(31)	–51(70)	26(36)	–89(122)	23(31
Birch							
Entire coutry	120	–27(67)	20(49)	–11(27)	20(49)	–22(54)	19(47)
Area 1	120	–16(39)	20(49)	–8(20)	20(49)	–15(37)	20(49)
Area 2	120	–17(42)	20(49)	–5(12)	20(49)	–14(34)	20(49)
Area 3	120	–33(81)	20(49)	–12(30)	20(49)	–28(69)	19(47)
Area 4	120	–82(202)	21(52)	–33(81)	21(52)	–69(170)	20(49)
All tree species							
Entire coutry	711	–5(7)	26(36)	9(12)	30(41)	–3(4)	27(37)
Area 1	711	3(4)	27(37)	13(18)	30(41)	5(7)	27(37)
Area 2	711	9(12)	27(37)	18(25)	30(41)	10(14)	27(37)
Area 3	711	–13(18)	26(36)	6(8)	30(41)	–11(15)	26(36)
Area 4	711	–63(86)	23(31)	–18(25)	30(41)	–57(78)	24(33)

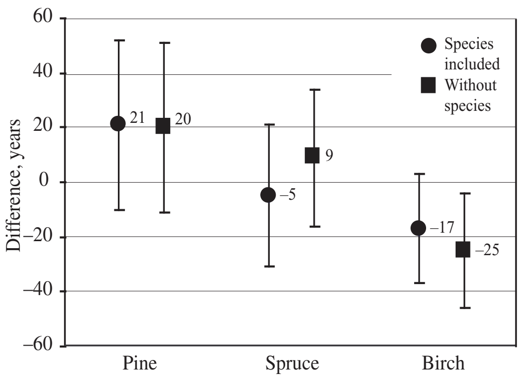

Fig. 5. Averages and standard deviations for predicted values of age = f(h) for area 2 with and without information on trees species.

deviation was smallest for Norway spruce and largest for birch when evaluated in a relative unit of measure (Table 13).

The influence of tree species was studied by comparing models formulated for all tree species with species-specific models using the test data from area 2. The predictions of the latter models differed only slightly from the former for Scots pine, whereas the differences were considerable for Norway spruce and birch (Fig. 5). The need for ecoregions was tested using the combined model in which the observations from all regions were included as with diameter models. Test results for model age = f(h) by tree species are presented in Table 14. The differences between the areas were mostly statistically significant for the models age = f(h), age = $f(d_{crm})$ and age = $f(h, d_{crm})$. Only a few combinations of model

Table 14. F-tests of the regional differences of age models: Age=f(h) by tree species.

Ecoregion pair	Full model			Reduced model			n	F-value
	df_F	SSE_F	MSE_F	df_R	SSE_R	MSE_R		
Pine								
Combined	5291	803.1368	0.151793	5300	1008.076	0.190203	5303	150.014*
Area1–Area2	1963	312.6647	0.159279	1966	319.9468	0.16274	1969	15.240*
Area1–Area3	2764	414.8875	0.150104	2767	416.0185	0.15035	2770	2.512
Area1–Area4	816	117.2568	0.143697	819	134.5371	0.16427	822	40.085*
Area2–Area3	4475	689.9734	0.154184	4478	789.9237	0.176401	4481	216.084*
Area2–Area4	2527	387.7959	0.153461	2530	569.5738	0.225128	2533	394.841*
Area3–Area4	3328	505.7562	0.15197	3331	552.7361	0.165937	3334	103.047*
Spruce								
Combined	3649	372.1469	0.101986	3658	522.388	0.142807	3661	163.684*
Area1–Area2	2278	184.5613	0.081019	2281	185.2537	0.081216	2284	2.849*
Area1–Area3	1298	170.6416	0.131465	1301	183.8495	0.141314	1304	33.489*
Area1–Area4	275	33.6570	0.122389	278	75.4370	0.271356	281	113.790*
Area2–Area3	3374	338.3279	0.100275	3377	411.4739	0.121846	3380	243.152*
Area2–Area4	2351	199.0333	0.084659	2354	299.6171	0.12728	2357	396.035*
Area3–Area4	1371	184.9698	0.134916	1374	215.3127	0.156705	1377	74.967*
Birch								
Combined	2270	270.6566	0.119232	2279	351.08	0.15405	2282	74.946*
Area1–Area2	904	106.2435	0.117526	907	106.6052	0.117536	910	1.026
Area1–Area3	1223	146.1228	0.119479	1226	148.8303	0.121395	1229	7.553*
Area1–Area4	215	22.8635	0.106342	218	37.6083	0.172515	221	46.218*
Area2–Area3	2055	248.281	0.120818	2058	276.6014	0.134403	2061	78.135*
Area2–Area4	1047	125.0935	0.119478	1050	195.2979	0.185998	1053	195.864*
Area3–Area4	1366	166.066	0.121571	1369	200.2231	0.146255	1372	93.655*

* Significant F-value.

form and tree species formed exceptions on some pairs of areas. There were only minor differences between the trees species.

5 Discussion

The primary aim of the modelling was to develop a part of the chain of models required for a new inventory method based on measurements of tree height and maximum crown diameter obtained from high-resolution aerial photographs by digital photogrammetry (Korpela 2000, 2004) combined with information available from existing stand databases and forest plans. The models could also be utilized when airborne laser scanning data is available. The idea is to predict the diameter at breast height for a single tree by using information derived from aerial photographs and forest plans, which will in turn enable its volume to be calculated. This will mean that the volume of growing stock for a sample plot can be derived from an aerial photograph. Number of independent variables were tested during the study. For example, the number of dominant trees per hectare could be derived from remote sensing data, but it didn't improve the estimation results. According to the tests, the best third variable in the models was basal area. The coefficients of the determination for models with three variables were only slightly better than for those with two variables; thus the benefit achieved with a third variable is negligible. The effect of the third variable was minor also in validation phase of study.

Models for predicting the diameter at breast height for a single tree were formulated here based on field data only. Traditionally, aerial photography based volume models are constructed using photogrammetric height and crown width measurements for specific image material. However, the imaging condition and visibility of tree dimensions differ according to the scale of photograph and the relative position of the tree in the aerial photograph. When multiple photographs are utilized, crown dimensions can be measured from several sources, improving the process (Korpela 2004). Laser scanning is one of the most promising technologies in remote sensing-based forest inventories. Stand mean tree height and crown dimensions can be measured relatively accurately from airborne laser scanning data (Hyyppä et al. 2001, Næsset 2004), but further estimation of tree parameters is still required. Mainly these models are planned to be utilised with tree specific procedures, although stand specific procedures could utilise models to estimate mean size of trees. When allometric tree models are created using field measurements, like in this study, separate calibration models can be used to relate remote sensing-based measurements and ground measurements with improved accuracy.

Because the data set used for modelling contains random measurement errors, the estimated coefficients are biased (Kangas 1998). The statistical tests of the coefficients may also be invalid. However, the coefficients, that are clearly significant remain significant even when measurement errors are taken into account. If the significance is less clear, changes in significance may occur. The effect of random measurement errors on the models can be evaluated by using, for example, the simulation extrapolation method (Carroll et al. 1995). Because no measurement error information is available in the data set, the error effect here is evaluated based on existing studies. The standard error of height using a Suunto hypsometer is, for instance, according to Päivinen (1992) 7.1 dm (3.4%) and Hyppönen and Roiko-Jokela (1978) 8.0 dm (5.7%). No crown diameter measurement error information is available for using the Kajanus tube. If the error of height measurement is assumed to be 5% and the error of crown diameter measurement to 10%, both of which are reasonable, it would be possible to estimate the effect of the maximum error of diameter at breast height.

The models for Norway spruce being the best in terms of RMSE was somewhat unexpected, as according to Ilvessalo (1950), the diameter at breast height can be determined most accurately for Scots pine, the predictions for Norway spruce and birch being much weaker. Scots pines and birches also grow on poor sites, especially on the coast and in northern Finland, where Norway spruce is not found, and seem to produce rather abnormal stem forms there. This could explain the superiority of the Norway spruce models.

The small, young trees (height < 3 m) are a weak point in the models formulated here, and prediction of their diameter at breast height is not necessarily always reliable. On the other hand, these small trees will not be a problem when using the models in an inventory chain if only because they tend to be obscured by the older growing stock in aerial images. An inventory of sapling stand is, of course another matter. The difference in the case of small trees is obviously due to their not having had to compete with adjacent trees for growing space and light, so that the relations between tree variables are slightly different from those for a tree at a later stage of development (Jakobsons 1970). Young trees should therefore have models of their own. Damaged and diseased trees were not included in the modelling. The allometric characteristics do not work well with broken or damaged trees, which mean that these objects should be identified somehow from the remote sensing material. The identification could be based on exceptional allometric features or spectral features in aerial photography.

The applicability and validity of the models was tested with small data set collected from subarea. The conclusion with regard to the modelling of diameter at breast height was the same as that reached by Talts (1977): that crown width is not very reliable as the only independent variable. For example, the heights of the Norway spruces defined the diameter very well, although the crown diameter was not such a particularly good independent variable, at least partly on account of the shaded character of spruces. Tree height was better for this purpose, but it was only when both were used that a reasonable prediction was obtained. This also increased the flexibility of the models, allowing them to take into account the state of competition in the growing stock and its density. Use of models that have at least tree height and maximum crown diameter as independent variables is therefore recommended. To ensure reliability, a division of the country into areas, i.e. regional models, should also be used.

The test results of the models indicated the same. The prediction of tree age proved to be challenging task. For all tree species, the standard deviation of age prediction was large.

The age models were constructed because tree age is an important criteria in defining need for silvicultural treatment. It is important that age estimated are also available in addition to tree size and stand density estimation, when forest information system is used for silvicultural planning. For conifers, the age of the tree was dependent most on its height, and for birch, the maximum crown diameter was the most important independent variable. Relative RMSE of age models for entire country was about 10%. Precision of models was improved significantly when ecoregion specific models were applied. Age prediction for birch was especially difficult. According to the tests, only maximum crown diameter should be used as an independent variable.

Although it is technically possible to measure crown width, crown projection area and crown length on aerial photographs, only the proportion of the crown which is visible can be measured, and the actual maximum crown width can not always be seen because of neighbouring trees. The resolution and visibility of small branches and irregular crown parameters are also dependent on the scale of photograph. One important issue is thus to examine the difficulties encountered in measuring crowns in different stand structures and under varying imaging conditions, involving at least changes in sun-target angle, wind, film and scanning quality. The final estimates can also be affected by local topographical variation. Thus, numerous factors can potentially cause error in photogrammetric forest inventories. The models might behave wrongly when those are applied with unexpected combination of independent variables. Still, the modelling data set is covering entire area of Finland and measurement of permanent sample plots of NFI are carefully collected, which should ensure that most of existing variation of target area is modelled properly. However, the models constructed here serve the need to estimate tree characteristics from crown dimensions from different remote sensing materials and will reduce the need for fieldwork in single tree-based forest inventory procedures.

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