Modelling Stand Mean Height in Young Naturally Regenerated Stands – a Case Study in Järvselja, Estonia

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Abstract

A classic approach to obtain stand height H_{Dq} in advanced stands in Estonia has to use the regression height at the quadratic mean diameter Dq. In juvenile stands, where a considerable number of young trees have not reached breast height, the modelling of the height distribution instead of the breast height diameter *dbh* distribution is more practical. Also, the field assessment methodologies differ for juvenile and advanced stands. In younger stands the mean height and stem number are assessed. In advanced stands (dbh larger than 6 cm) these variables are replaced with the basal area, quadratic mean diameter and the regression height. This study evaluates the predictive abilities of different mean height calculation functions in various tree species in naturally regenerated stands. We analyze different young stand height calculation methods in comparison with the classical stand height H_{Dq} calculation method. Two independent sets of empirical materials were employed in our study: 27 plots from Estonian Network of Forest Research Plots (ENFRP) were used in regression analysis and three forest regeneration study areas (45 plots) at Järvselja (JS plots) were used for model validation. In the current study the r-power mean height H_r ($H_r = \sqrt[r]{\left(\sum h^r\right)/n}$ where the exponent r value 3.627 estimated on 27 ENFRP plots) was fitted to the regression height H_{Dq}. We recommend using the dominant tree selection method for measuring stand height in juvenile stands. Our results indicate that the ratio of dominant trees k and stand component cluster dominant height H_k are adequate for calculating stand height in young stands as follows $H_{Dq} = a_1 \cdot H_k^{a_2} \cdot k^{a_3}$.

Key words: height distribution, mean height, dominant height, Scots pine, Norway spruce, Silver birch

Introduction

There is a number of univariate growth functions with asymptote and inflection points that are recommended for modelling the development of height over age (Kiviste 1988, Zeide 1993, Shvets and Zeide 1996). In addition, the fitted model should have biological interpretation (Vanclay and Skovsgaard 1997); however, in young stand as in this study, where height growth has not reached the inflection point, the widely used growth functions may give unrealistic height growth projections and are not suitable for height growth modelling.

Stand development predictions in time often depend on reliable height-diameter functions requiring height as the basic input variable (Temesgen and Gadow 2004). Stand height can be described in several ways: as mean-unweighted, mean-weighted, predominant, top and dominant height. Stand mean height-unweighted (or arithmetic average height) is rarely used, as its estimation requires measuring every tree height in the stand, which is possible to carry out in stands with height not more than 2–3 m (Krigul 1972). In some cases sample tree heights or tree heights from subsamples can be used for lowering the field assessment costs. Missing heights are obtained indirectly – using a suitable height-diameter relationship (e.g. Larsen and Hann 1987, Temesgen and Gadow 2004). To describe stand's growth and yield, usually the stand dominant height is used, instead of stand average height. The advantage of dominant height is that it is relatively unaffected by thinning, when (normal) thinning operations remove the smaller trees or dying trees (Vaus 2005).

The development of stand height can be presented by using a 3- parameter, asymptotic function, such as the Chapman-Richards function (Pienaar and Turnbull 1973). Studies in Unites States have shown that stand average dominant height can be accurately predicted using a percentage of the diameter distribution, when arranged in decreasing size order (Bailey and Brooks 1994, Bailey and Martin 1996). This technique using standard inventory data has been successfully applied to slash pine (*Pinus elliottii* Engelm.) (Bailey and Brooks 1994) and loblolly pine (*Pinus taeda* L.) (Bailey and Martin 1996) plantations. Brooks (2004) tested this methodology and estimated the stand dominant height for young longleaf pine (*Pinus palustris* P. Mill.) plantations.

In Europe, generalized height-diameter functions have been used since the 1930's. The generalized height diameter function includes both single tree level variables as individual tree heights and diameters, together with stand level variables like basal area and quadratic mean diameter (Gadow and Hui 1999, Temesgen and Gadow 2004). To calculate Lorey's mean height the stand height is weighted by the stand basal area to avoiding being affected by both natural and anthropogenic disturbances (Laar and Akēa 2007).

Describing young stand development is a challenge, as growing conditions in young stands are changing rapidly. Still, it is the most crucial period for modelling or for management planning since in this period the stand properties will be set for the entire rotation period. Forest growth modelling in the Nordic and Baltic countries has focused on advanced or mature stands. Very often the growth in early stands is predicted by using the same models as for mature stands. The evaluation of young stand height thus usually leads to over- or underestimation (Huuskonen and Miina 2007).

A classic approach to obtain stand height H_{Dq} in advanced stands in Estonia has to use regression height prediction at the quadratic mean diameter D_q. Accordingly, all tree heights are calculated using the height regression function. Depending on differences in height growth and tree ingrowth in juvenile stands, the time during which a considerable number of seedlings have not reached breast height can be very long (especially in naturally regenerated stands). Therefore, modelling of the height distribution instead of the breast height diameter (dbh) distribution is technically more advisable. Another important aspect is that the field assessment methodologies are different for juvenile and advanced stands (Siipilehto 2009). In younger stands mean height and stem number are assessed. In advanced stands (dbh larger than 6 cm) these variables are replaced with basal area, quadratic mean diameter and regression height.

More functional and realistic height projections are needed for the early stand development phase in Estonia. Height growth has only been studied for the fast-growing tree species (*Betula pendula* Roh., *Alnus incana* L. Moench., *Alnus Hybrida* A. Br., *Populus × wettsteinii* Hämet-Ahti) planted on former agricultural lands (Jõgiste et al. 2003, Vares et al. 2003). The evaluation of stand height in young stands is needed to assign to the changing requirements of forest management planning.

The aim of this paper is to evaluate the predictive abilities of different mean height calculation functions in various tree species in naturally regenerated stands. In our study, we analyze the different young stand height calculation methods in comparison with the classical stand height H_{Dq} calculation method.

Material and methods

Estonian Network of Forest Research Plots

The Network of Estonian Forest Research Plots (ENFRP) was established in 1995 (Kiviste et al. 2003) to provide empirical data for developing forest growth and yield models (Kiviste and Hordo 2003). The network establishment is based on the experience of Finnish studies (Gustavsen et al. 1988). Following the grid of ICP Forest level I monitoring plots (Karoles et al. 2000), the ENFRP contains 730 in 5-year interval remeasured sample plots, distributed with random placing in two- to ten-plot clusters over the entire land surface of Estonia (Figure 1). Most plots are in heath, mesotrophic, meso-eutrophic, and nemoral forest site types.

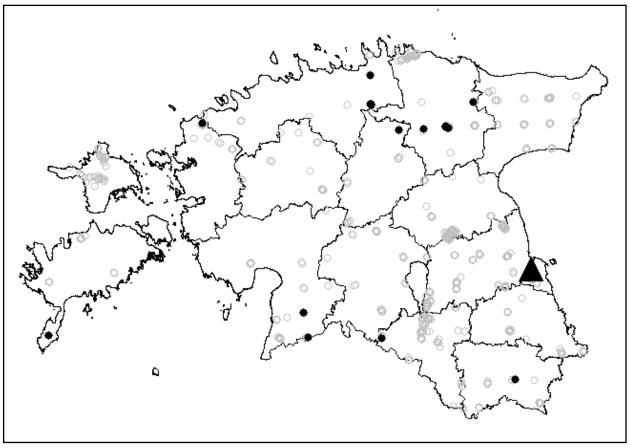

Figure 1. Spatial distribution of all ENFRP plot clusters (one cluster includes 2 to 10 plots group) across Estonia (empty circles) together with the locations of the 27 plots (filled circles) in this study. The filled triangle indicates the location of Järvselja Training and Experimental Forest Centre

The plots are circular with varying radii (15, 20, 25 or 30 metres) and each plot includes at least 100 main storey trees. Second-storey and undergrowth trees are measured in an inner circle with a radius of 8 or 10 metres depending on the main plot radius. In each plot for all trees the tree coordinates are fixed and breast height diameters are measured. In addition, the total tree height and crown length of selected sample trees (every fifth tree) are also measured (Kiviste and Hordo 2003). In Estonia, the concept of stand component is used to describe different tree species forming a certain stand layer (e.g. second layer spruce). The age for different stand components is determined by the date of establishment of the stand component, which is during the first plot measurement by counting tree rings from core samples extracted from sample trees. The plots are remeasured in five-year intervals.

Table 1. Stand component data from the ENFRP plots

Tree species	Number of stand compo-nents	Min H_{Dq}, m	Max H_{Dq}, m	Min k	Max k	Number of trees	Number of sample trees	Single tree height, m		
								min	mean	max
all	42	4.31	13.11	0.125	0.833	1759	859	1.4	7.9	18.4
all conifers	20	4.31	11.59	0.125	0.833	722	444	1.4	6.5	16.6
all broadleaves	22	4.40	13.11	0.222	0.763	1037	415	2.9	8.9	18.4
pine	6	4.31	11.59	0.372	0.730	317	170	1.4	5.7	16.6
spruce	14	4.58	10.94	0.125	0.833	405	274	2.1	7.2	13.4
birch	15	4.40	11.26	0.282	0.763	875	356	3.0	8.9	15.8
broadleaves (birch excluded)	7	7.43	13.11	0.222	0.667	162	59	2.9	8.5	18.4

In single tree and stand level height calculations, data from 27 ENFRP plots were used which corresponded with the set criteria: 1) plot radius is greater than or equal to 14 metres; 2) maximum height of dominant trees in the main storey is less or equal to 15 metres; 3) the mean age of the main storey is less than or equal to 20 years. In the 27 selected plots, 5,125 single tree measurements (with 1,308 height measures) were distributed between 88 different stand components. The stand characteristics of the simulated plot clusters are presented in Table 1. These include 1,759 single tree measurements for 42 stand components.

Regeneration study plots at Järvselja

A series of nine study areas (JS plots) was established in 2005 in south-eastern Estonia at the Järvselja Training and Experimental Forest Center (58°25´N, 27°46´E) for study of the growth dynamics in young naturally regenerated forests.

Sample areas were divided into three different young stands and are located together in stands depending on stand size in one, three and five study groups. Nine sample areas were distributed within stands at even intervals of 50 metres. The sample plots inside the study areas were located using cluster arrangement as shown in Figure 2. Every cluster included five circular 50 m^2 size plots (radii = 4 m).

The center of the middle plot in a cluster was set in the center of a study area. The other four plots were located 10 metres away to the north, south, east and west. The plot centre was marked with a metal pole. Furthermore, all plots were divided into four sectors (each 12.5 m^2) following the north-south and west-east axes. Each sector was numbered, starting from the northeast quarter.

From the center of the middle plot in the cluster, at a distance of 5, 10 and 15 metres to north, south, east and west, the depth of soil organic matter excluding moss and lichen layer was defined. Data describing site characteristics were recorded according to Lõhmus's (2004) classification.

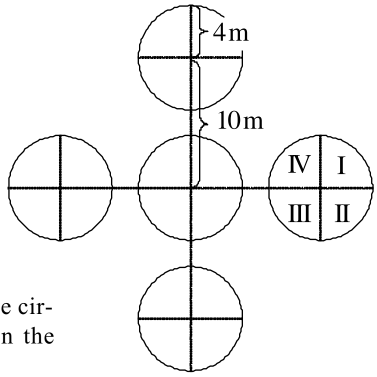

Figure 2. A design of five circular plots cluster within the study areas

During the first four measurement occasions we measured height for all trees higher than 0.8 metres from the ground level. Beginning in 2008 all tree heights were measured starting from the ground level. The tree records at each re-measurement included sector number, tree layer, tree species and total tree height. Within each sample plot sector, three highest sample trees were selected from the dominant tree species. In addition, one sample tree was selected for every other tree species found in the sector. For each sample tree higher than 1.3 metres, dbh in two directions (to plot center direction and perpendicular), total height, the height of living crown base and height of lowest dead branch (thickness = 2 cm, length = 10 cm) were measured. Damages, classified according to cause and severity, on the sample trees were recorded. In addition, tree coordinates were assessed from the center of cluster for all sample trees.

Table 2. Stand component data from Järvselja plots

Tree species	Number of stand components	Tree height, m Min	Tree height, m Max	Number of trees
all	146	0.05	13.90	10086
all conifers	43	0.80	10.90	1819
all broadleaves	103	0.05	13.90	8267
pine	7	0.80	2.87	38
spruce	36	0.80	10.90	1781
birch	36	0.79	12.80	3973
aspen	18	0.41	13.90	2425
linden	15	0.05	7.70	912
other broadleaves	34	0.80	6.80	957

The stands were measured in July and August in 2005, and re-measured at the end of the vegetation period (September or October) in 2006, 2007 and 2008. The four different measurement periods were considered in data analyzed independently, including in total 10,086 single tree measurements distributed between 146 stand components. The general stand component data are presented in Table. 2.

Modelling

Simulation of single tree heights on the ENFRP plots

On the ENFRP plots a tree height is measured for every 5th tree; however, for simulating the JS plot establishment on ENFRP data, tree heights must be predicted for all trees. For simulation of tree height, an equation (Eq. 1) consisting of fixed and random components was applied (Padari 1999):

$$h_s = 1.3 + a\left(\frac{dbh}{dbh + b}\right)^c + \varepsilon \qquad (1)$$

where h_s is simulated tree height (m), *dbh* is diameter at breast height (cm), *a* and *c* are model parameters estimated from sample tree data for each of 42 stand components, *b* is a tree species dependent constant (1.1 for pine, 1.3 for spruce, 8.0 for birch, 1.6 for ash and 4.3 for other broadleaves), *å* is random variable with normal distribution $\varepsilon = N(0;SE)$, SE is residual standard error.

For estimation of parameters *a* and *c*, Eq. 1 was transformed into a linear regression equation as follows:

$$\ln(h - 1.3) = \ln(a) + c \cdot \ln\left(\frac{dbh}{dbh + b}\right) \qquad (2)$$

The simulated tree heights h_s were used in following calculations as real tree height.

Sample trees selection and sample trees mean height calculations on ENFRP plots

The cluster selection system similar to the one used in JS plots was simulated for the plots from ENFRP. From each simulated sector (Figure 2) the two highest trees (regardless of species) were selected. Thus each sample plot cluster included up to 40 single tree heights. Obtained heights were grouped by stand components and for every group six different means (Eq. 3 … Eq. 8) were calculated as cluster dominant heights for juvenile stands.

For testing the effect of using different methods in calculating cluster dominant height, the following six equations were used:

$$H_{quad} = \sqrt{\frac{\sum h_i^2}{n}} \qquad (3)$$

$$H_{sqrt} = \left(\frac{\sum \sqrt{h_i}}{n}\right)^2 \qquad (4)$$

$$H_{arit} = \frac{\sum h_i}{n} \qquad (5)$$

$$H_{cube} = \sqrt[3]{\frac{\sum h_i^3}{n}} \qquad (6)$$

$$H_{geom} = \exp\left(\frac{\sum \ln(h_i)}{n}\right) \qquad (7)$$

$$H_{harm} = \frac{n}{\sum \frac{1}{h_i}} \qquad (8)$$

where H_{quad} is quadratic mean height, H_{sqrt} is square root mean height, H_{arit} is arithmetic mean height, H_{cube} is cubic mean height, H_{geom} is geometric mean height, H_{harm} is harmonic mean height, h_i is measured tree height and *n* is number of trees.

Combining simulation combinations

To assess the relationship between the classical regression height (H_{Dq}) calculation method for advanced stands in Estonia and cluster dominant height in juvenile stands, we begain by predicting regression height (H_{Dq}) for simulated plot clusters as follows:

$$H_{Dq} = 1.3 + a\left(\frac{Dq}{Dq + b}\right)^c \qquad (9)$$

where H_{Dq} is regression height of the tree with the quadratic mean diameter for stand component (m), *Dq* is stand component quadratic mean diameter (cm), *a* and *c* are regression coefficients (Eq. 2) and *b* is a tree species dependent constant (Eq. 1). The estimates of parameters *a* and *c* were re-estimated for the simulated data.

On a stand level four different regression equations (Eq. 10 … Eq. 13) were used to analyze H_{Dq} predictions in case of six different means for cluster dominant mean height (Eq. 3 … Eq. 8)

$$H_{Dq} = a_1 + a_2 \cdot H_k + a_3 \cdot k \tag{10}$$

$$H_{Dq} = a_1 + a_2 \cdot H_k + a_3 \cdot k + a_4 \cdot H_k \cdot k \tag{11}$$

$$H_{Dq} = a_1 \cdot H_k^{a_2} \cdot k^{a_3} \tag{12}$$

$$H_{Dq} = a_1 \cdot H_k^{a_2} \cdot k^{a_3} + a_4 \cdot H_k \cdot k \tag{13}$$

where H_{Dq} is stand component regression height (m), H_k stand component cluster dominant height (arithmetic, quadratic, cubic, harmonic, square root or geometric), k is ratio of number of sample trees to total number of trees, and a, b, c, d are model parameters.

The first two regression equations (Eq. 10 … Eq. 11) are linear whereas the two last (Eq. 12 … Eq. 13) are nonlinear. According to these functions *lm* and *nls* were used for parameter estimations with R software (Crawley 2007).

The simulation was carried out by combining the four different model forms (Eq. 10 … Eq. 13) with six different transformations of cluster dominant height calculations (Eq. 3 … Eq. 8) for seven different tree species or tree species groups. Descriptive statistics of 42 stand components from the 27 ENFRP plots are presented in Table 1.

For each regression equation (Eq. 10 … Eq. 13) and tree species or tree species group, the best performing cluster dominant height calculation combination were selected.

Model validation on Järvselja data

The selected 28 equations were used in validation of JS plots and were used in the mean height calculations for each stand component on JS data (see Table 2).

The obtained stand component's mean height calculated from cluster dominant height H_k and ratio k were intended for comparison with the corresponding regression height H_{Dq} on JS data. On the Järvselja plots, the tree heights are measured for all the trees, but the diameters are measured only for selected sample trees; therefore, it is not possible to compute mean height H_{Dq} directly. For this study, mean height H_{Dq} was considered equivalent to r-power mean of tree heights H_r (Eq. 14)

$$H_r = \sqrt[r]{\frac{\sum h_i^{\,r}}{n}} \tag{14}$$

where H_r is r-power mean height (m), r is exponent term, n is number of measured tree heights, h_i is single tree height (m).

The relationship between r-power mean height and regression height was studied on the basis of ENFRP plots. Optimal exponent term r was estimated for each tree species or tree species group.

The r values estimated on ENFRP plots were used for calculating r-power mean height as a substitute for the missing regression height for JS data. For evaluating simulation combinations, their predictions were compared with the corresponding r-power mean heights (H_r) using the paired t-test. Three criteria were set to better distinguish between simulation combinations: 1) the quadratic mean difference (SE) is less than 0.8 m, 2) the mean difference is less than 0.10 m and 3) p-value from t-test of differences exceeds 0.05.

In addition, a test was carried out on JS data to clarify the sample tree selection preferences for selected stand mean height models. Five different sample trees selection methods were used, where:

- from each plot sector the two tallest trees were selected (N_{st2});
- from each plot sector the three tallest trees were selected (N_{st3});
- from each plot sector the four tallest trees were selected (N_{st4});
- from each plot sector the six tallest trees were selected (N_{st6});
- the sample trees were selected as in JS field measuring (N_{streal}).

Results and discussion

This study presents the stand height prediction functions which show the closest relation to the commonly used regression height H_{Dq} for naturally regenerated young stands employing the cluster dominant stand component height H_k and the ratio k between number of selected dominant trees and total tree number as predictor variables. Regression height H_{Dq} is not directly applicable to stands where the trees have not reached breast height (Siipilehto 2009). An alternative approach based on single tree height distribution is offered for obtaining the r-power mean height (H_r) as a stand height in young stands being the closest to classically used stand height (H_{Dq}).

Tree selecting simulation on ENFRP plots according to the cluster selection method used in field sampling in JS plots resulted in a total of 1,759 single tree samples divided among 42 different stand components. These selected trees were used for model selection for three main tree species (Scots pine, Norway spruce and silver birch) and four tree species groups (all trees together, all conifers together, all broadleaves together, and all broadleaves together excluding birch (Table 1)). The dataset covered a range of tree heights from 1.4 m to 18.4 m.

Model selection and parameter estimation

All combinations of four regression equations (Eq. 10 … Eq. 13), six mean height equations (Eq. 3 … Eq. 8) and seven tree species or tree species groups were used for modelling regression height H_{Dq} with predictor variables H_k and k on ENFRP data. For the 28 best calculation combinations (*CN*), fit statistics including adjusted determination coefficient (R^2), residual standard error (*SE*) value and parameter estimates on ENFRP data are presented in Table 3.

Table 3. Best performing models by tree species and model shape. CN – combination number

CN	Eq. no.	Tree species	Number of stand components	Mean height	R^2	SE, m	Regression constants			
							a_1	a_2	a_3	a_4
1	(10)	all	42	H_{arit}	0.943	0.573	–0.2613	0.9100	1.4112	–
2	(10)	all conifers	20	H_{arit}	0.934	0.618	0.2441	1.0048	–0.3801	–
3	(10)	all broadleaves	22	H_{arit}	0.978	0.340	–1.2748	0.9264	3.0596	–
4	(10)	pine	6	H_{arit}	0.999	0.122	–0.8980	0.9952	1.3909	–
5	(10)	spruce	14	H_{arit}	0.887	0.725	0.6870	0.9657	–0.4930	–
6	(10)	birch	15	H_{arit}	0.985	0.293	–0.9602	0.9128	2.5027	–
7	(10)	other broadleaves except birch	7	H_{arit}	0.979	0.368	–0.9169	0.8269	4.8750	–
8	(11)	all	42	H_{arit}	0.962	0.475	3.6449	0.4268	–5.9945	0.9130
9	(11)	all conifers	20	H_{arit}	0.938	0.618	3.6089	0.4777	–5.6548	0.8019
10	(11)	all broadleaves	22	H_{arit}	0.983	0.304	1.5968	0.6166	–2.7526	0.6234
11	(11)	pine	6	H_{arit}	1.000	0.039	3.5549	0.1745	–5.7712	1.2925
12	(11)	spruce	14	H_{arit}	0.915	0.660	9.5843	–0.4068	–13.6933	1.9932
13	(11)	birch	15	H_{arit}	0.988	0.281	0.8598	0.7149	–1.2718	0.4119
14	(11)	other broadleaves except birch	7	H_{arit}	0.990	0.297	3.9534	0.2991	–4.2968	0.9769
15	(12)	all	42	H_{arit}	0.968	0.559	1.1917	0.9339	0.0933	–
16	(12)	all conifers	20	H_{arit}	0.996	0.611	0.9861	1.0005	–0.0369	–
17	(12)	all broadleaves	22	H_{arit}	0.897	0.320	1.1549	0.9670	0.1609	–
18	(12)	pine	6	H_{arit}	0.990	0.108	1.0536	1.0023	0.1429	–
19	(12)	spruce	14	H_{arit}	0.985	0.722	1.0920	0.9557	–0.0354	–
20	(12)	birch	15	H_{arit}	0.896	0.284	1.1262	0.9672	0.1396	–
21	(12)	other broadleaves except birch	7	H_{arit}	0.841	0.373	1.5938	0.8562	0.2204	–
22	(13)	all	42	H_{arit}	0.957	0.511	0.6094	0.9250	–0.2921	0.6176
23	(13)	all conifers	20	H_{arit}	0.980	0.586	0.6293	0.9782	–0.2904	0.4744
24	(13)	all broadleaves	22	H_{arit}	0.888	0.315	0.7905	0.9657	–0.0376	0.4020
25	(13)	pine	6	H_{arit}	0.984	0.115	0.5683	1.0054	–0.2302	0.5526
26	(13)	spruce	14	H_{arit}	0.963	0.721	0.7635	0.9179	–0.2512	0.4270
27	(13)	birch	15	H_{arit}	0.884	0.286	0.7821	0.9664	–0.0602	0.3738
28	(13)	other broadleaves except birch	7	H_{arit}	0.800	0.315	1.0127	0.7152	–0.1574	0.7653

The first two linear regression equations (Eq. 10 and Eq. 11) might not give realistic predictions for stand early development (H_k less than four meter tree height); however, nonlinear regression equations (Eq. 12 and Eq. 13) start always from zero and therefore we can assume their near reality prediction even in case of very small trees (H_k less than breast height 1.3 m).

It is important to note that of the six different mean height calculations, only the arithmetic mean height (H_{arit}) seems to work with all equations and tree species. The cubic mean height (H_{cub}) gave the poorest fit results in mean height calculation combinations. On the other hand, using H_{arit} as the sample trees height distribution has to the least effect on stand mean height H_k calculations versus other mean heights.

According to the results presented in Table 3, the residual standard errors (*SE*) are as follows: Eq. 10: 0.12–0.73 m, Eq. 11: 0.04–0.66 m, Eq. 12: 0.11–0.72 m and Eq. 13: 0.12–0.72 m. Norway spruce showed significantly higher residual standard errors (ranging from 0.66–0.73 m) than SE values for other tree species (the highest SE value is 0.37 m). The poor fit of spruce can be explained by the irregular height distribution in young stands caused by new spruce regeneration coexisting with advanced regeneration.

Calculation of r-power mean height for juvenile stands

Based on the data from ENFRP plots, the regression height H_{Dq} and r-power mean height H_r for r values from 3.0 to 4.0 by 0.1 were calculated according to Eq. 14 for all stand components. Relationships between average difference of $(H_r – H_{Dq})$ and exponent r for different tree species and tree species groups are presented in Figure 3.

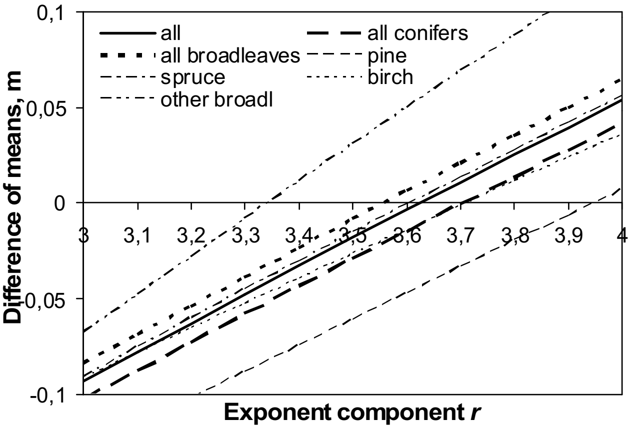

Figure 3. The average difference between regression height of the tree with the quadratic mean diameter and r-power mean height on the data of ENFRP plots depending on exponent r

Estimations of exponent term r for different tree species or tree species groups were chosen where the difference between regression height H_{Dq} and r-power mean height was zero (Figure 3) and are presented in Table 4. The exponent r estimations vary depending on tree species. For Scots pine and silver birch the estimated r values are higher than for Norway spruce. This can be explained by different tree species dependent height distribution and height-diameter relationships. At the same time the difference between regression height H_{Dq} and r-power mean height is the lowest for Scots pine.

Evaluation of selected model combinations with dominant tree selection on JS data

For evaluation of 28 selected model combinations (see Table 3) an independent JS dataset was employed. The total number of individual tree heights used for the height prediction comparison with *r-power* mean height was 10,086 divided among 146 stand components. The JS dataset covered a range of tree heights from 0.05 m to 13.90 m (Table 2).

Table 4. Comparison results for mean heights (regression height of the tree with the quadratic mean diameter and exponent mean height) with paired t-test

Tree species	Exponent component r	Quadratic mean difference, m	Mean of the differences	95% confidence intervals	
				lower	higher
all	3.627	0.153	–0.000024	–0.048	0.048
all conifers	3.706	0.183	0.000050	–0.088	0.088
all broadleaves	3.558	0.120	–0.000045	–0.054	0.054
pine	3.949	0.078	0.000000	–0.089	0.089
spruce	3.608	0.210	–0.000071	–0.126	0.126
birch	3.712	0.118	–0.000067	–0.068	0.068
other broadleaves	3.343	0.124	0.000143	–0.124	0.124

For all 146 JS stand components H_{Dq} was predicted using different simulation combinations (CN from Table 3) according to: 1) tree species specific parameter combinations CN (Eq. 10) = 4, 5, 6, 7; CN (Eq. 11) = 11, 12, 13, 14; CN (Eq. 12) = 18, 19, 20, 21 and CN (Eq. 13) = 25, 26, 27, 28, 2) broadleaves and conifers group specific parameter combinations CN (Eq. 10) = 2, 3; CN (Eq. 11) = 9, 10; CN (Eq. 12) = 16, 17 and CN (Eq. 13) = 23, 24 and 3) generalized parameter combinations CN (Eq. 10) = 1; CN (Eq.11) = 8; CN (Eq. 12) = 15 and CN (Eq. 13) = 22. The r-power mean height (Eq. 14) was calculated following the model combinations for every obtained stand component H_{Dq} as a reference height for t-test comparison. Five different dominant height sample tree selection methods (see Table 5) were applied to all simulation combinations and are presented in Tables 6, 7 and 8).

The comparison results (Tables 6, 7 and 8) between r-power mean height and predicted H_{Dq} values showed better performance with model combinations where the third (Eq. 12) equation was used. The tree species or species group vise analysis indicated that there are no considerable differences in predictions when using species specific or general model combi-

Table 5. Sample tree totals by selection method

Tree species	Number of trees	Number of sample trees				
		N_{st2}	N_{st3}	N_{st4}	N_{st6}	N_{streal}
all	10086	1351	1956	2494	3393	2494
all conifers	1819	330	492	621	798	663
all broadleaves	8267	1021	1464	1873	2595	1831
pine	38			2	6	23
spruce	1781	330	492	619	792	640
birch	3973	625	881	1090	1461	989
aspen	2425	322	468	601	810	560
linden	912	20	31	55	103	77
other broadleaves	957	54	84	127	221	205

Table 6. Standard errors between *r*-power mean height (H_r) and estimated mean height. *CN* indicates the model combination according to Table 4. *Bold* indicates the differences that are less than 0.8 m

CN	SE				
	N_{st2}	N_{st3}	N_{st4}	N_{st6}	N_{streal}
1	***0.581***	***0.541***	***0.501***	***0.484***	***0.481***
8	1.856	1.704	1.621	1.446	1.521
15	***0.517***	***0.490***	***0.452***	***0.408***	***0.412***
22	1.685	1.387	1.154	***0.702***	***0.630***
2, 3	***0.797***	***0.768***	***0.693***	***0.707***	***0.770***
9, 10	1.250	1.129	1.055	0.933	0.932
16, 17	***0.700***	***0.598***	***0.493***	***0.444***	***0.482***
23, 24	0.915	***0.764***	***0.580***	***0.432***	***0.453***
4…7	0.876	0.856	0.880	1.126	1.087
11…14	2.400	2.219	2.021	1.727	1.871
18…21	***0.790***	***0.677***	***0.557***	***0.501***	***0.563***
25…28	1.169	1.011	0.874	***0.681***	***0.647***

Table 7. Average difference (m) between *r*-power mean height (H_r) and estimated mean height (H_{Dq}). *CN* indicates the model combination according to Table 3. *Bold* indicates the differences that are less than 0.1 m

CN	Average difference (H_r–H_{Dq}), m				
	N_{st2}	N_{st3}	N_{st4}	N_{st6}	N_{streal}
1	0.291	0.233	0.264	0.236	0.150
8	1.513	1.181	0.921	0.368	0.575
15	0.271	0.200	0.200	***0.095***	***0.042***
22	1.017	0.711	0.572	0.297	0.288
2, 3	***–0.054***	***–0.086***	***–0.018***	***0.026***	–0.142
9, 10	0.882	0.647	0.494	0.127	0.204
16, 17	0.120	***0.042***	***0.037***	***–0.058***	–0.121
23, 24	0.395	0.245	0.194	***0.054***	***0.009***
4…7	0.134	0.145	0.249	0.423	0.240
11…14	1.729	1.466	1.218	0.768	0.935
18…21	0.178	0.125	0.137	***0.087***	***0.017***
25…28	0.740	0.557	0.503	0.359	0.327

nations in predicting stand mean height. Following the parsimonious principle (Burkhart 2003) to select the recommended simulation combination for predicting stand component mean height closest to regression height H_{Dq} in juvenile stands:

$$H = 1.192 \cdot H_k^{0.934} \cdot k^{0.093} \tag{16}$$

where H_k is arithmetic mean of cluster selected dominant trees, k is ratio of number of sample trees to total number of trees

Table 8. T-test p-values between *r*-power mean height (H_r) and estimated mean height. *CN* indicates the model combination according to Table 3. *Bold* indicates p-values more than 0.05

CN	T-test p-values				
	N_{st2}	N_{st3}	N_{st4}	N_{st6}	N_{streal}
1	6e-09	6e-07	7e-11	1e-09	0.0001
8	<2e-16	<2e-16	1e-12	0.0027	3e-06
15	1e-09	2e-06	1e-07	0.0060	***0.2139***
22	4e-13	1e-09	2e-09	2e-07	6e-09
2, 3	***0.4734***	***0.2157***	***0.7612***	***0.6736***	0.0249
9, 10	<2e-16	3e-12	2e-08	***0.1158***	0.0088
16, 17	***0.0622***	***0.4338***	***0.3965***	***0.1268***	0.0021
23, 24	1e-06	0.0003	9e-05	***0.1449***	***0.8154***
4…7	***0.0974***	***0.0597***	0.0010	6e-06	0.0072
11…14	<2e-16	<2e-16	2e-14	1e-07	2e-10
18…21	0.0135	0.0387	0.0043	0.0417	***0.7115***
25…28	1e-14	3e-11	5e-13	3e-11	7e-11

For all measured tree heights the 3.627-power mean is preferable:

$$H = \sqrt[3.627]{\frac{\sum h_i^{3.627}}{n}} \tag{17}$$

where H is stand component mean height (m), n is number of measured tree heights, h_i is single tree height (m).

It is quite evident and expected that with the higher number of sampled trees the stand dominant height predictions are better. However, we must be careful when comparing the stand mean height predictions between different sample tree selection methods, because in *r*-power mean height calculations the N_{st2} sampling method was used. The analysis of several sample tree selection methods revealed positive tendencies in species dependent sampling when comparing species independent tree sampling to dominant stand mean height prediction. The species dependent cluster selection method applied in ENFRP plots compared favorably against the real selection on JS plots, where in addition to the two highest sample trees from dominating species one tree was sampled from each co-dominating species in a particular plot sector, resulting in better prediction with lower sample tree number.

Due to natural regeneration, in stands with high spatial variation of the trees in each plot the tree sampling must take this variation into account. Otherwise, the selection might not reflect reality and the predictions will be biased. An example of such selection is presented on Figure 4 where Norway spruce

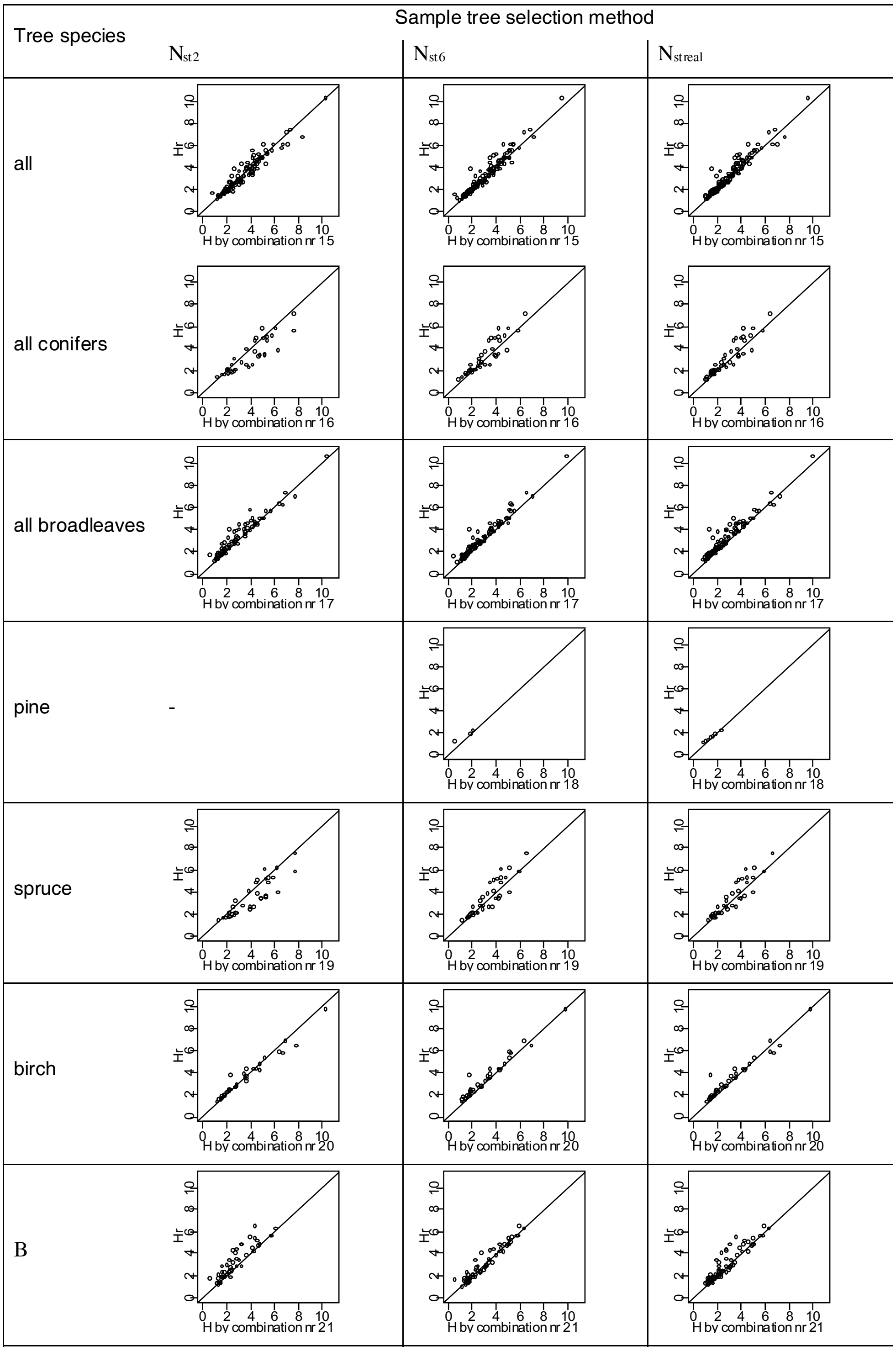

Figure 4. *r*-power mean height (H_r) and estimated stand mean height (H_k) for different tree species and tree species groups depending on sample tree selection method. The line represents a relationship between H_r and H_{Dq} predictions of 1:1

stand mean height calculations based on two tree sampling N_{st2} are underestimated versus using higher sample tree numbers. This indicates that for stands where different species are present and their spatial arrangement varies, the cluster dominant height can become lower than mean height of the particular stand component.

Conclusions

Due to missing breast height diameter data in juvenile stands, it is reasonable to use tree height distribution-based stand mean height instead of classically used regression height (H_{Dq}). In this study the *r*-power mean height H_r (Eq. 14) was fitted to regression height H_{Dq} and the exponent r value 3.627 was estimated on 27 ENFRP plots.

We recommend using the dominant tree selection method (where the two highest trees are measured per 12.5 m^2) for measuring stand height in juvenile stands. Following the dominant tree selection method and based on our results Eq. 12 is adequate for calculating stand height in young stands (estimated model parameters are presented in Table 3).

The species dependent cluster selection method shows better prediction for lower sample tree numbers when in addition to the two highest sample trees from dominating species a single tree is sampled from each co-dominating species on a plot.

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References

Bailey, R.L. and Brooks, J.R. 1994. Determining site index and estimating timber volumes without measuring heights. *Southern Journal of Applied Forestry* 18: 15–18.

Bailey, R.L. and Martin, S.W. 1996. Predicting dominant height from plantation age and the diameter distribution n-site-prepared loblolly pine. *Southern Journal of Applied Forestry* 20: 148–150.

Brooks, J.R. 2004. Predicting and projecting stand dominant height from inventory data for young longleaf pine plantations in southwest Georgia. In: Connor, K.F. (ed.), Proc. of the 12th biennial southern silvicultural research conference, Asheville, NC: U.S. Department of Agriculture, Forest Service, Southern Research Station, 600 p.

Burkhart, H.E. 2003: Suggestions for choosing an appropriate level or modelling forest stands. In: Amaro, A., Reed, D. and Soares, P. (eds.), Modelling forest systems. CAB International, 3–10.

Crawley, M.J. 2007: The R Book. John Wiley & Sons Ltd, 942 p.

Gadow, K.v. and Hui, G.Y. 1999. Modelling forest development. Kluwer Academic Publisher, Dordrecht, 213 p.

Gustavsen, H.G., Roiko-Jokela, P. and Varmola, M. 1988. Kivennäismaiden talousmetsien pysyvät (INKA ja TINKA) kokeet. Suunnitelmat, mittausmenetelmät ja aineistojen rakenteet. The Finnish Forest Reserch Institute. Research Papers 292. (In Finnish).

Huuskonen, S. and Miina, J. 2007. Stand-level growth models for young Scots pine stands in Finland. *Forest Ecology and Management* 241: 49–61.

Jõgiste, K., Vares, A,. and Sendrós, M. 2003. Restoration of former agricultural fields in Estonia: comparative growth of planted and naturally regenerated birch. *Forestry* 76: 209–219.

Karoles, K., Õunap, H., Pilt, E., Terasmaa, T. and Kivits, H. 2000. Forest condition in Estonia 1988–1999, defoliation and forest damages on Level I sample points. Air pollution and forests in industrial areas of north-east Estonia. *Metsanduslikud Uurimused / Forestry Studies* 33: 209–216.

Kiviste, A. 1988. Forest Growth Functions. Estonian Agricultural Academy, Tartu, 108 (in Russian)

Kiviste, A. and Hordo, M. 2003. The network of permanent sample plots for forest growth modeling in Estonia. In: Markevica, A., Lypsik, A., Leep, R. (eds.), Research for Rural development 2003. International Scientific Conference Proceedings, Jelgava, p. 174–177.

Kiviste, A., Nilson, A., Hordo, M. and Merenäkk, M. 2003. Diameter distribution models and height-diameter equations for Estonian forests. In: Amaro, A., Reed, D. and Soares, P. (eds.), Modeling forest systems. CAB International, p. 169–179.

Krigul, T. 1972. Metsatakseerimine [Forest mensuration]. Tallinn, 358 p. (in Estonian).

Laar, A.V. and Akēa, A. 2007. Forest mensuration. *Managing forest ecosystems* vol. 13. Springer, Dordrecht, 383 p.

Larsen, D.R., and Hann, D.W. 1987. Height-diameter equations for seventeen tree species in southwest Oregon. Forest Research Laboratory, Oregon State University, Corvallis. Research Bulletin 49, 16 p.

Lõhmus, E. 2004. Eesti metsakasvukohatüübid [Estonian forest site types]. Eesti Loodusfoto, Tartu, 80 p. (in Estonian).

Padari, A. 1999. Kasvava metsa hindamisest. Sortimendid ja rikked [About the assessment of the growing forest. Assortments and defects]. EPMÜ Metsandusteaduskonna toimetised nr. 32. Pidev metsakorraldus. Tartu, 37–43 (in Estonian).

Pienaar, L.V. and Turnbull, K.J. 1973. The Chapman–Richards generalization of von Bertalanffy's growth model for basal area growth and yield in even-aged stands. *Forest Science* 19: 2–22.

Shvets, V. and Zeide, B. 1996. Investigating parameters of growth equations. *Canadian Journal of Forest Research* 26: 1980–1990.

Siipilehto, J. 2009. Modelling stand structure in young Scots pine dominated stands. *Forest ecology and management* 257: 223–232.

Temesgen H. and Gadow, K.v. 2004. Generalized height-diameter models: an application for major tree species in complex stands of interior British Columbia. *European Journal of Forest Research* 123: 45–51.

Vanclay, J.K. and Skovsgaard, J.P. 1997. Evaluating forest growth models. *Ecological Modelling* 98: 1–2.

Vares, A., Uri, V., Tullus, H. and Kanal, A. 2003. Height growth of four fast-growing deciduous tree species on former agricultural lands in Estonia. *Baltic Forestry* 9: 2–8.

Vaus, M. 2005. Metsatakseerimine. [Forest mensuration]. Halo Kirjastus, Tartu, 178 p. (in Estonian).

Zeide, B. 1993. Analysis of growth equations. *Forest Science* 39: 594–616.

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МОДЕЛИРОВАНИЕ СРЕДНЕЙ ВЫСОТЫ МОЛОДЫХ НАСАЖДЕНИЙ НА ПРИМЕРЕ ЛЕСНИЧЕСТВА ЯРВСЕЛЬЯ, ЭСТОНИЯ

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Резюме

Классическим подходом предсказания роста насаждений в Эстонии является средняя высота (регрессионная высота) со средним квадратичным диаметром H_{Dq} в обобщенной функции высоты и диаметра. В молодняках, имеющих естественное происхождение, где значительное количество саженцев ещё не достигло высоты груди, вместо моделирования распределения диаметра более практичным является моделирование высоты. Кроме того, методы измерения среднего роста насаждений в лесу для саженцев и молодых насаждений отличаются. В молодняках с диаметром менее 6 см оценивается средняя высота насаждений и количество деревьев. В то время как в молодняках с диаметром более 6 см используются сумма площадей поперечных сечений насаждения, регрессионная высота и средний квадратичный диаметр деревьев. В ходе исследования были оценены прогностические возможности различных методов калькуляции средней высоты для разных пород деревьев в насаждениях восстанавливающихся естественным путем. Были сравнены различные методы вычисления средней высоты насаждений классическим методом. В нашем исследовании были использованы две независимые выборки эмпирических данных: 27 участков эстонской сети лесных пробных площадей (ENFRP) были использованы для регрессионного анализа, а данные с трёх зон (45 пробных площадей) в Ярвселья, где проводиться исследование лесовосстановления, были использованы для проверки модели. В данной работе, r-степенная средняя высота H_r (функция 14) была оценена для 27 участков эстонской сети лесных пробных площадей (ENFRP) и сравнена с регрессионной высотой H_{Dq}. Для измерения высоты молодых насаждений (диаметр менее 6 см) можно рекомендовать доминирующие деревья изучаемых секторов, наилучшие результаты дала функция 12.

Ключевые слова: распределение высоты, средняя высота, доминирующая высота, сосна обыкновенная, ель обыкновенная, берёза повислая