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Validation of Generalized Height-Diameter Model Based on Lithuanian NFI Data

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Abstract

The height estimation of every tree included in NFI sample plots is based on height-diameter ratio measurements of small amount of subsample trees. Height is measured for systematically selected every seventh tree on the sample plot (Kuliešis et al. 2003a, 2009b). On average, height and diameter of 1–7 trees of prevailing and 1–3 trees of admixture tree species are measured per one plot. Heights of the remaining trees are estimated using generalized height-diameter model (Kuliešis 1993) based on measured diameters of all trees as well as height-diameter ratio of subsample trees. The goal of this study is to estimate the accuracy of tree height prediction using generalized height-diameter model based on measurement of height-diameter relation of small amount of subsample trees. This study makes use of the data of height-diameter ratio measurements on 1998–2010 NFI plots. This data derives from 47.5 thousand subsample trees of prevailing eight tree species as follows: pine, spruce, birch, aspen, black alder, grey alder, oak, and ash, and 24.6 thousand subsample trees of the same tree species as admixture in stands. Deviations of modeled heights from measured ones and their significance were estimated in respect of tree species, tree position – prevailing or admixture, mean diameter, and mean height. Spruce and oak stands have the most, and black alder and aspen stands have the least tree height variation per group with the range of mean diameter ± 2 cm and the range of mean height ± 1 m. Accuracy of mean tree height estimation per plot shifts from 3–5% in stands with mean diameter equal to 40 cm and more up to 5–15% in stands with mean diameter equal to 4–20 cm. Mean height deviations of predicted values from those obtained by measuring all tree populations on stand is negligible for all species, -0.6 cm per prevailing tree, -2.5 cm per admixture tree and -1.3 cm per any tree. Differences between predicted and measured height both of prevailing and admixture trees of all species are statistically insignificant (probability level 0.95). Tree species were divided into two groups with different character of height deviations for trees with diameter lower or larger than mean diameter of stand. Systematical deviations up to 9–20 (33) cm were estimated for predicted heights of trees with diameter up to and over the mean diameter in pine, oak, birch and black alder stands, while in spruce, aspen, grey alder and ash stands such deviations had random character not exceeding 6–9 (24) cm. While all the system in general (sampling design and model) used for tree height estimation during NFI can be given a positive evaluation, some height estimation improvements for prevailing pine and spruce trees less than 7 m high and admixture birch trees less than 5 m high should be done by modifying the generalized height-diameter model applied.

Key words: generalized height-diameter model, subsample trees, predicted heights, accuracy

Introduction

Measurement of tree height is time consuming to compare with that of tree diameter at 1.3 m height, (*hereinafter* diameter) and other measurements during forest inventory. Small amount of subsample trees is commonly used for estimation of relationship between height and diameter and for prediction of height of every remaining tree by regression equation. A lot of studies are dedicated to the investigation of height and diameter relationship in order to develop the most efficient equations (Loetsh and Haller 1964, Larsen and Hann 1987, Huang et al. 1992, Pretzsch 2010). Special attention is paid to elaboration of regional (Trincado et al. 2007, Sharma and Parton 2007, Schmidt et al. 2011) and generalized models (Temesgen and Gadow 2004, Dorado et al. 2006) allowing to exploit local or more generalized peculiarities of height and diameter relationship and to estimate height of trees more precisely with less measurements and lower costs. It is crucial to employ most reliable methods of height estimation during NFI for proper representation of large-scale forest regions. It is typical to use small amount sampling plots and small amount of subsample trees for estimation of height-diameter relationship in national forest inventories (Tompo et al. 2010, Kuliesis et al. 2010). For reliable prediction of every tree height, using common regression functions, it is necessary to measure minimum 5–7 sample trees per each object (plot, stand). Having 20–30 trees and 3–5 different species per each plot would mean measurement of height of almost all trees in the plot, what is expensive and ineffective.

Analysis of height-diameter ratio conducted by measuring 8.9 thousand trees in 4,126 plots during the inventory of state forests of Lithuania by sampling method in 1969, proved it being possible to generalize height-diameter relationship for trees of the same species growing in the same storey of stand (Кулешис 1981a, 1983b, 1992c). Generalized height-diameter relationship models were elaborated for the 8 main tree species. The basis for generalized model was conclusion that pattern of height-diameter relationship in ratio terms depends mainly on mean diameter of trees in the stand. Rate of height in relative terms convexity and steepness of curves is decrease with the increase of adequate diameter of trees (Figure 1). The equation describes the family of curves defining relationship among relative height, relative diameter and mean diameter of stands. All curves in relative terms of stands with different mean diameter have common point at mean diameter and mean height of stand. The model elaborated was tested over the wide growth area of the species represented (Scots pine growth area subjected to testing spread from the Northern regions of Russia to Poland in the South and Siberia in the East (Третьяков и др. 1952, Суприянович и др. 1975), that of Norway spruce – from Norway (Vestjordet 1972), the Northern and Central Russia (Третьяков и др. 1952, Захаров и др. 1931) to Czech Republic, Poland and Ukrainian Carpathians (Šmelko 1983, Bruchwald and Rymer-Dudzinska 1981, Цурик 1981), and that of birch and aspen included the Northern and Central Russia (Третьяков и др. 1952, Тюрин 1931)). The differences between heights predicted by model and those specified in regional tables or models did not exceed ± 1.3–2.0% (Кулешис 1983). Generalized height-diameter relationship model was approved and recommended for tree height prediction in even-aged stands at forest inventory in different regions of the former Soviet Union (Кулешис 1992) and was fully introduced into forest inventory practice of Lithuania (Medienos… 1997). Generalized height-diameter model can be adopted for tree height prediction of individual stand, if the mean diameter of stand and minimum diameter and height of one representative tree is known. These were key parameters of generalized height-diameter relationship model applied in Lithuanian forest inventories by sampling methods (Kuliešis et al. 2003a, 2009b). The model has been used for prediction of tree heights from the beginning of Lithuanian NFI in 1998 (Kuliešis et al. 2010).

The goal of this study is to optimize tree height estimation system in sampling design of Lithuanian NFI, to investigate the accuracy of generalized height-diameter relationship model applied in NFI from 1998 through 2010 for tree height estimation in stands of eight main Lithuanian forest tree species (*Pinus sylvestris* L. (*hereinafter* Pine), *Picea abies* (L.) *H. Karst.* (*hereinafter* Spruce), *Betula pendula Roth* (*hereinafter* Birch), *Populus tremula* L. (*hereinafter* Aspen), *Alnus glutinosa* (L.) *Gaertn.* (*hereinafter* Black alder), *Alnus incana* (L.) *Moench* (*hereinafter* Grey alder), *Quercus robur* L. (*hereinafter* Oak), *Fraxinus excelsior* L. (*hereinafter* Ash) and to explore possibilities of further development or improvement of the model. The above made it necessary to solve the following tasks:

1. To estimate the statistical tree height parameters, which are necessary for optimization of forest inventory sampling design;
2. To estimate deviations of tree height predicted by the model based on mean tree diameter, mean height of stand (plot) and diameter of trees from the measured one, separately for prevailing and admixture trees;
3. To estimate significance of deviation-bias of height predicted by the generalized model from the measured height and to evaluate the necessity to correct the generalized model.

Material and Method

The object of study are trees of eight forest tree species dominating in forest stands of Lithuania, as represented by permanent plots of NFI 1998–2010 as well as generalized model of height-diameter relationship used for height prediction. The study included all trees, both prevailing and admixture ones, of eight tree species (Table 1). The species with the largest total basal area of trees or growing stock volume per storey of stand is called prevailing, while all other species as admixture. Heights were measured for every seventh systematically selected tree per plot. For trees of admixture species positioned in different stories, height of at least one tree was measured. Trees with larger diameter were preferred for height measurements because of less height variation in stand. Every subsample tree with measured height and diameter was used for mean height estimation of trees of specific species and storey per plot. On an average, height and diameter of 1–7 trees of prevailing and 1–3 trees of admixture tree species from different storeys are measured per plot. Trees with diameter 2.1 cm and more as well as more than 1.3 m high, growing in stands with mean quadratic diameter of 2.1 cm and more, were included in the study, making up the total of 72 074 subsample trees measured on 6 101 plot.

Table 1. General statistics regarding diameter at breast height (D, cm) and total height (H, m) of tree species involved in the study

Species		Number of plots	Number of subsample trees	D, cm				H, m			
				Stand		Subsample trees		Stand		Subsample trees	
				Mean	Range	Mean	S.D.	Mean	Range	Mean	S.D.
Pine	prevailing	2078	18584	20.89	2–56	26.47	9.55	21.62	1–35	23.20	5.76
	admixture		5506	15.57	2–56	24.32	9.98	20.71	1–35	23.08	6.28
Spruce	prevailing	1102	7379	16.65	2–56	25.02	10.21	20.16	1–33	23.04	6.40
	admixture		4727	14.58	2–56	24.80	11.04	21.08	1–37	23.23	6.56
Birch	prevailing	1279	8585	13.72	2–56	23.00	9.67	20.70	1–33	23.56	6.52
	admixture		6096	15.28	2–56	23.81	10.04	19.58	1–33	22.10	6.28
Aspen	prevailing	409	2372	14.97	2–56	27.74	12.08	24.30	3–35	26.36	7.39
	admixture		2535	15.46	2–56	24.14	10.08	21.04	1–33	23.10	6.22
Black alder	prevailing	597	5039	15.37	2–50	21.63	7.69	18.03	3–31	19.68	4.79
	admixture		2796	14.23	2–56	23.35	9.65	19.16	1–31	21.62	5.62
Grey alder	prevailing	396	4201	10.84	2–30	16.47	5.72	14.59	3–25	16.84	4.25
	admixture		1452	12.84	2–46	23.31	10.65	17.68	1–29	20.57	5.84
Oak	prevailing	136	651	28.70	2–64	40.11	17.65	22.87	3–33	24.47	5.94
	admixture		848	19.52	2–54	27.74	10.71	21.74	1–31	23.44	5.97
Ash	prevailing	104	693	18.71	2–56	28.09	11.31	22.35	3–33	24.28	5.80
	admixture		610	15.26	2–56	26.11	11.49	20.98	1–31	22.99	6.39
Total	prevailing	6101	47504	17.63		24.75		20.51		22.61	
	admixture		24570	15.15		24.28		20.25		22.58	

Generalized height-diameter relationship model (Figure 1) is defined by regression equation

$$R_{hi} = 1 - (a_0 + a_1D + a_2D^2) + (b_0 + b_1D + b_2D^2) \cdot (R_{di}+e)^{-1} + (c_0 + c_1D + c_2D^2) \cdot (R_{di}+e)^{-2}, \qquad (1)$$

where coefficients a_i, b_i, c_i, and e are estimated for all eight main tree species of Lithuanian forests according to Кулешис 1981a, 1983b, D is a mean quadratic diameter of trees per stand, d_i is the tree diameter at 1.3 m height, R_{hi} is the ratio of i-th tree height (h_i) and the mean height of trees (H), adequate to the mean quadratic diameter in the stand,

$$R_{hi} = h_i/H, \qquad (2)$$

R_{di} is ratio of i-th tree diameter and mean quadratic diameter of trees in the stand

$$R_{di} = d_i/D. \qquad (3)$$

Mean tree height of stand, as a function of mean quadratic diameter of stand (D), can be predicted by Equation 1, when height (h_i) and diameter (d_i) of a subsample tree is known (Figure 2)

$$H_i = h_i/R_{hi}. \qquad (4)$$

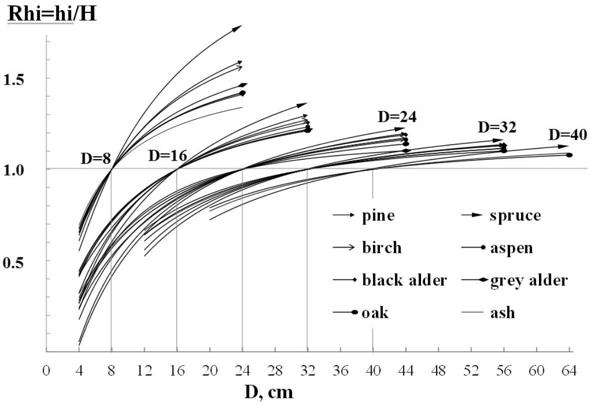

Figure 1. Generalized height-diameter model

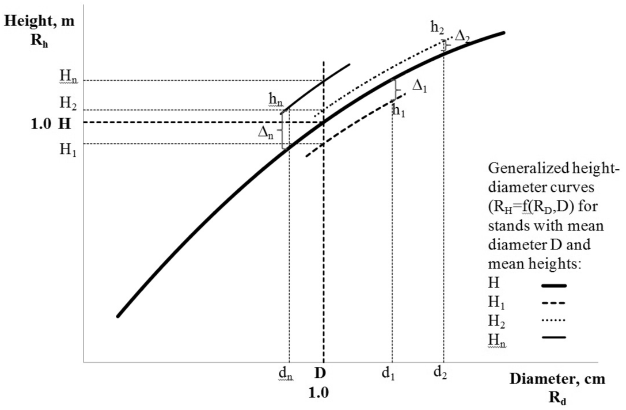

Figure 2. The scheme of estimating mean height of stand (plot) (H) by use of generalized height-diameter model based on mean diameter of trees in stand (plot) (D) as well as diameter (d_i) and height (h_i) of the subsample trees measured

Having measured heights of n subsample trees, likely the mean tree height of the stand. can be estimated:

$$H = \Sigma H_i/n. \qquad (5)$$

The mean quadratic diameter and mean height for prevailing and admixture tree species in every sample plot of NFI were estimated. Ratios R_{di} and R_{hi}, predicted height (h_{ip}) and its deviation (Δ_i) from the measured height were estimated for every subsample tree:

$$h_{ip} = H \cdot R_{hi}, \qquad (6)$$

$$\Delta_i = h_{ip} - h_i. \qquad (7)$$

The following method was applied to estimate the significance of differences between the predicted and measured heights of trees (Гмурман 1972):

$$\Delta = \frac{\sum_{i=1}^{n} h_{ip} - h_i}{n}. \qquad (8)$$

The difference of the two mean values is estimated statistically as:

$$t = \frac{\Delta}{\sigma_{(h_{ip} - h_i)}} \qquad (9)$$

where $\sigma_{(h_{ip}-h_i)}$ is a standard deviation of the difference between the mean values:

$$\sigma_{(h_{ip}-h_i)} = \sqrt{\frac{\sigma^2_{h_{ip}} + \sigma^2_{h_i}}{n}} \qquad (10)$$

where: $\sigma_{h_{ip}}$, σ_{h_i} are estimated standard deviation between the predicted and measured tree heights, n is the number of measurements.

Differences between values of the predicted and measured heights are significant when:

$$t > t\alpha \qquad (11)$$

$t\alpha$ is statistics of t value under probability α, t_{0683}= 1, $t = {}_{0,95} \approx 2,0$ (Cochran 1963, Fišas 1968).

If the values of the predicted and measured height are within the limits of confidence interval, it can be stated that differences are statistically insignificant. On the contrary, when the parameters compared are beyond the range of confidence interval, this implies that differences are statistically significant.

Subjects of estimation were mean diameter of all trees in plot and mean height corresponding to mean diameter as well as differences between the predicted and measured height of subsample trees of every species in the plots. All plots were grouped by 4 cm mean diameter and 2 m mean height steps. Every such sub–group forms up a primary cell of investigation. Statistical characteristics (means, variances, coefficients of variation, correlation) of diameter and height of measured trees and the statistical significance of deviation of predicted heights from the measured ones using Student's statistic t were estimated for every primary cell as well as the totals by the mean diameter and mean height of trees. The LOESS, a nonparametric regression method. was used to estimate the major trends of deviation of the predicted heights from the measured ones (Cleveland 1979). Deviations of the predicted heights from the measured ones for trees, which are thinner and thicker than the mean diameter per cell, were estimated separately. Data was processed using 'Statistica' software package.

Results

Variation of tree height in the stand. Mean diameters of pine, spruce, birch, aspen and ash stands included in the permanent plots of NFI in Lithuania vary in the range of 2 to 56 cm, those of oak stands – up to 64 cm, and those of grey alder – up to 30 cm for prevailing trees and 46 cm – for admixture trees (Table 1). The range of mean diameter for prevailing and admixture trees is the same for most of species. The mean height of trees in stands of six main species attains 33–35 m, in stands of black alder – 31 m, and in grey alder stands – 25 m.

The standard deviation of subsample tree diameter in the most cases varies in the range of 9–12 cm (Table 1). Only for prevailing trees of oak stands this parameter exceeds this range and attains 17.65 cm, while the standard deviation of prevailing trees of grey alder stands is just 5.72 cm, and that of black alder – 7.69 cm. The standard deviation of admixture tree diameter exceeds the standard deviation of prevailing tree diameter for most of tree species with the exception of aspen and oak.

The height standard deviation of subsample tree height for most of species varies in the range of 5.7 – 6.6 m (Table 1). Height standard deviation of prevailing aspen trees attains value 7.39 m, while that of grey alder trees is only 4.25 m, and of black alder trees – 4.79 m. Height standard deviation of admixture trees exceeds the same of prevailing trees by 0.2–1.6 m, except for birch and aspen.

The height standard deviation of pine trees per each cell varies in the range of 1.1–4.0 m, averaging at 2 m (Table 2). Height standard deviation is a function of mean height and mean diameter of trees. In stands with constant mean diameter, height standard deviation slightly increases with increase of mean height, until attains maximum and after that decreases. For stands with constant mean height of up to 12 m, height standard deviation decreases with increase of mean diameter. For stands with mean height of 16 m and more, height standard deviation performs like in the stands with constant mean diameter, i.e. slightly increases with increase of mean diameter until maximum value and then decreases. The maximal height standard deviations are typical for stands with average mean height in every diameter group, that is, when mean diameter and mean height ratio is equal to 1.2–1.6. (Table 2). Mean height standard deviation of pine stands increases continuously from 2.2 to 4.2 m with increase of mean diameter of stands from 4 to 48 cm (Table 2).

The highest tree height standard deviation is characteristic of coniferous species and oak stands with mean diameter of 28–36 cm, while that of stands of broadleaved species is between 8 and 28 cm (Figure 3). Stands of spruce and oak are characterized by the highest tree height standard deviation amongst all of the species. The fastest decrease of standard deviation at the increase of mean diameter is typical of grey alder, aspen and birch trees. Starting from values of about 2.0–2.2 m, they attain the minimum standard deviation value of 0.8–1.0 m, when mean diameter of trees reaches 28–56 cm and more (Figure 3).

Table 2. Dependence of standard deviation of the measured pine tree height on mean diameter and mean height of trees (in numerator) and correlation between the measured and predicted heights (in denominator), when number of measured trees is more than 10

Mean diameter, cm	Mean height,m																
	2	4	6	8	10	12	14	16	18	20	22	24	26	28	30	32	Total
4	1.53	1.22															2.19
	0.64	0.80															0.90
8		1.08	1.29	1.80	2.44	2.27											2.94
		0.83	0.85	0.90	0.89	0.86											0.96
12			1.23	1.58	2.03	1.89	1.71	2.13	1.81								3.19
			0.90	0.79	0.85	0.82	0.86	0.83	0.79								0.95
16				1.66	1.73	2.10	2.05	1.97	1.90	1.85							3.26
				0.88	0.85	0.89	0.83	0.82	0.79	0.80							0.94
20					1.55	1.83	2.22	2.12	2.12	2.07	1.81	1.96					3.20
					0.77	0.72	0.77	0.78	0.79	0.79	0.77	0.75					0.91
24							1.66	2.71	2.34	2.22	2.19	2.13	2.32	2.27			3.16
							0.57	0.69	0.79	0.78	0.80	0.79	0.82	0.86			0.90
28								2.06	2.26	2.66	2.31	2.26	2.08	2.28			3.49
								0.75	0.75	0.80	0.81	0.81	0.80	0.80			0.92
32								2.12	2.12	2.60	2.75	2.30	2.15	2.24	1.94		3.71
								0.72	0.77	0.81	0.85	0.80	0.81	0.81	0.77		0.93
36									1.62	2.66	3.10	2.46	2.36	2.02	2.05	1.61	3.93
									0.65	0.80	0.85	0.81	0.80	0.74	0.71	0.82	0.93
40											3.96	2.62	2.51	2.12	1.86	2.81	3.96
											0.90	0.83	0.81	0.73	0.77	0.89	0.92
44												1.95	2.25	1.70	1.62	1.88	3.86
												0.67	0.80	0.67	0.68	0.78	0.94
48												1.50	1.38	1.63	1.11	1.24	4.22
												0.80	0.75	0.85	0.52	0.83	0.98
Total	1.53	1.14	1.51	1.66	2.06	1.98	1.97	2.10	2.10	2.22	2.25	2.24	2.20	2.13	1.87	2.14	5.76
		0.83	0.86	0.85	0.86	0.84	0.82	0.79	0.79	0.78	0.80	0.80	0.80	0.78	0.73	0.83	0.97

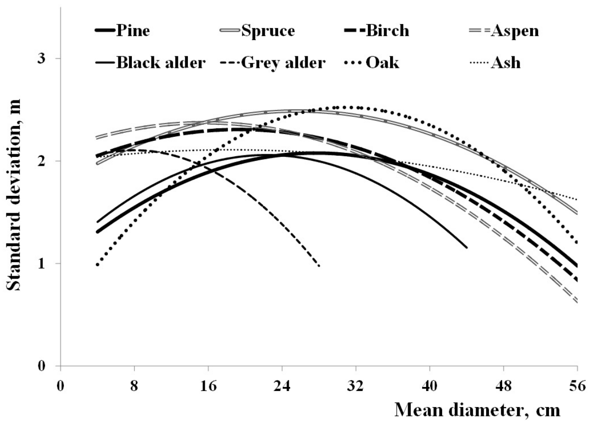

Figure 3. Standard deviation of tree height in a cell with range of mean diameter of stand equal to ± 2 cm and that of mean height equal to ± 1m, depending on mean diameter of stand and tree species

Dependence of tree height variation, expressed by coefficient of variation, on stand mean diameter and mean height is more definitive. Coefficient of variation decreases gradually with increase of mean diameter and mean tree height (Figure 4). The rate of variation coefficient decrease is similar for all species, except for oak (decreases more slowly) and grey alder (decreases faster) (Figure 5). The value of tree height variation coefficient is lowest at 7–8% in grey alder and ash stands and reaches 10% in aspen, 11% in birch and black alder, 13% in pine, and 15% in spruce stands, when mean diameter of stands is equal to 24 cm (Figure 5). Three zones with different tree height variation change rate can be distinguished. The first zone of intense decrease of variation coefficient with increase of mean diameter and mean height includes stands up to 20 cm in mean diameter. Tree height variation de-

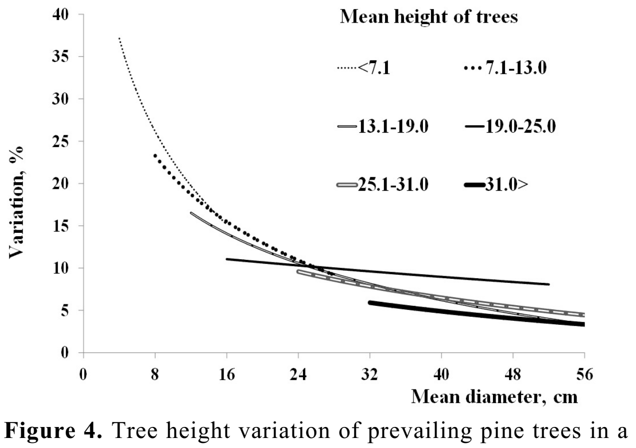

Figure 4. Tree height variation of prevailing pine trees in a cell (range of mean diameter of stand ± 2 cm, that of mean height ± 1 m) depending on mean diameter and mean height

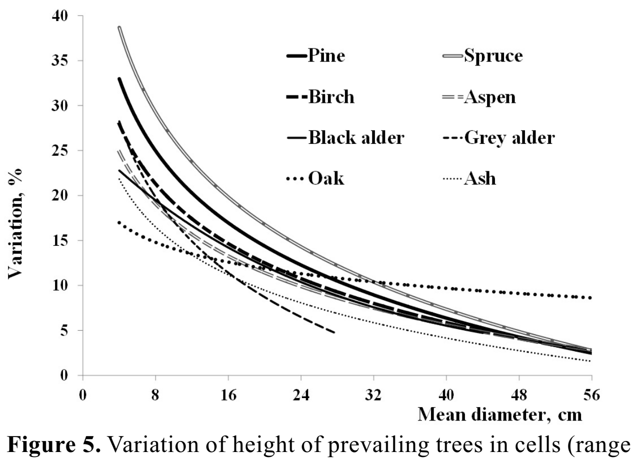

Figure 5. Variation of height of prevailing trees in cells (range of mean diameter of stand ± 2 cm, that of mean height ± 1 m) depending on mean diameter of stand and tree species

creases from 40 to 9%. Stands with mean diameter of 21–40 cm belong to the second zone, where height variation drops from 17 to 4%, and, finally, in stands with mean diameter over 40 cm, tree height variation comes down from 10 to 2%. The highest tree height variation is characteristic of spruce, in the second and third being pine and birch stands. Tree height variation of above mentioned tree species is in the range of 2–6%. The low tree height variation is typical of all soft broadleaved species and ash. The maximal tree height variation is 14% in stands with mean diameter of 8 cm, while the minimal one at 5% is observable in stands with mean diameter of 32 cm.

Curves representing height-diameter relationship in certain object, for example, the whole of pine stands of the country, change their shape and position, depending on mean diameter and mean height of stand (Figure 6). The pattern of height-diameter relationship curves as a function of individual mean diameter and mean height is essentially different from pattern of mean height-diameter relationship curve for the total object or its marginal curves.

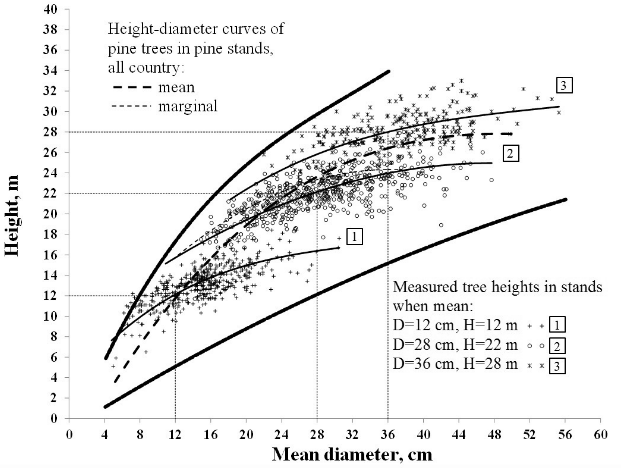

Figure 6. Comparison of tree height-diameter relationship in pine stands with different mean diameter (D) and height (H) of trees

Accuracy of mean height estimation in a NFI plot. Accuracy of height estimation depends mainly on the number of measured subsample trees and height variation in the stand (plot). Tree height variation in the plot is 3 to 40%. The number of subsample trees per plot in pine stands of certain mean diameter increases with increase of mean tree height, independently on mean diameter (Figure 7). The average number of measured trees per plot in stands varies from 1 to 7. The average number of due tree height measurements, independently on species, increases with increase of mean diameter up to 12–16 cm and then decreases up to 1–2 measurements (Figures 8).

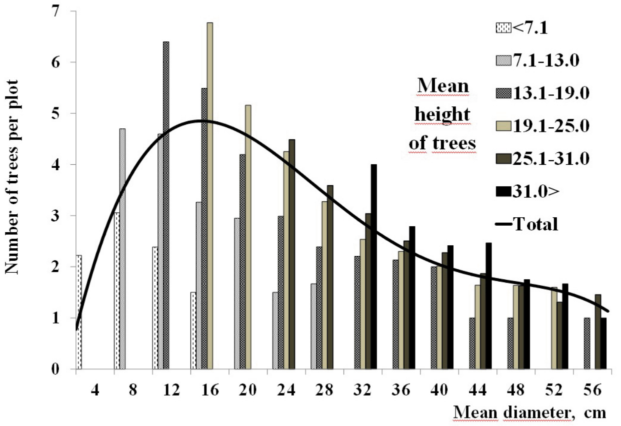

Figure 7. Number of subsample trees measured per plot for height estimation depending on mean diameter and mean height of pine stands

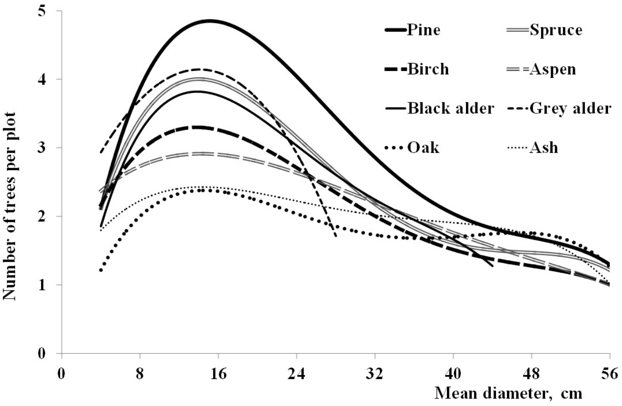

Figure 8. Number of subsample trees measured per plot for height estimation depending on mean diameter of stand and tree species

The highest number of measurements is due in pine and spruce stands, i.e. in stands of species with the highest tree height variation. Decrease of subsample tree height measurements per plot corresponds to the decrease of tree height variation, so as to satisfy acceptable accuracy of mean height estimation in wide enough range of mean diameter of stands. The mean standard error of height estimation in pine stands bears an inverse relation to the mean diameter and mean height of stands (Figure 9).

The standard error of height estimation holds a very strong inverse relation to mean diameter of stands (Figures 9 and 10). In stands of the first diameter group (mean diameter up to 20 cm) with the highest tree height variation the number of tree height measurements varies from 2 to 8, on average 4. This allows for 5–

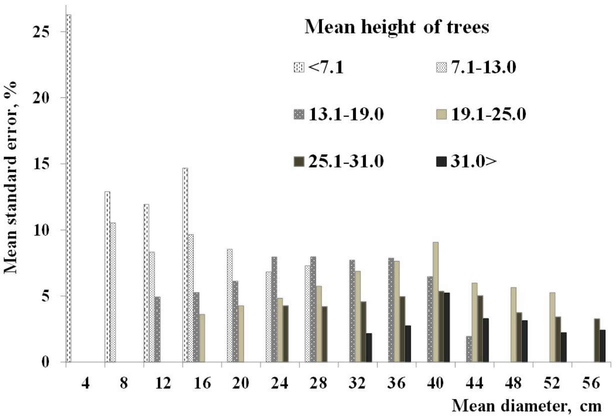

Figure 9. Accuracy of mean tree height estimation in sample plots of pine stands

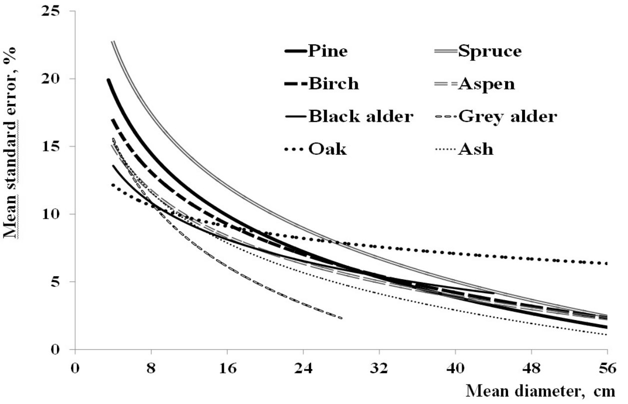

Figure 10. Accuracy of mean tree height estimation in sample plots depending on mean diameter of stand and tree species

20% mean standard error of plot mean height estimation, what approximately corresponds to 1 m (Figures 8, 9, 10).

For stands of the second diameter group (D = 20–40 cm) the number of tree height measurements per plot varies in the range of 2 to 6, what allows for 3–10% mean standard error, when estimating the mean height of a plot. This corresponds to approximately 1–1.5 m. The number of tree height measurements (1–3) per plot of the third diameter group allows for standard error of 3–7%, what is adequate to 0.7–1.5 m. Results of this analysis show that NFI sampling design of Lithuania allows to estimate the mean height of a plot with standard error of 0.7–1.5 m, independently on species. This precision is quite comparable to that of instrumental measurement. The highest accuracy of height estimation was received for plots of grey alder and ash stands, while the lowest one was received for spruce and especially oak stands with mean diameter exceeding 28 cm (Figure 10).

Deviation of predicted heights from measured heights. The deviations of predicted height from the measured one of pine trees were analyzed for three different periods (Table 3). Mean diameter and mean height of subsample pine trees in pine stands increased, on average, by 0.20 cm and 0.16 m per year correspondingly during the period of 1998–2010 (Table 3). This increase is a result of dominance of 60–80 years old pine stands and shortage of mature stands. This predetermines less intensive final cuttings, less percentage of young pine stands, and high accumulation of volume increment to compare with normal forest having equal areas of different age classes. The mean diameter and the mean height of pine admixture trees in stands of other species (spruce, birch) also increase with age but not so fast, correspondingly 0.16 cm and 0.13 m a year. It is a result of more intense final cuttings in stands of these species to compare with pine stands.

Analysis of deviations in various inventory cycles showed that mean deviation of predicted height from the measured one is very similar for pine trees in all inventory cycles (Table 3). The mean deviation of predicted pine trees' height from measured one in pine stands changes from -0.3 in 2008–2010 up to +1.4 cm in 1998–2002. The mean deviation during 1998–2010 inventory period per tree is 0.4 cm. The deviation of predicted height of pine trees present as admixture in stands of other species are very similar, they vary in the range of -0.8-2.7 cm and practically do not depend on trees' mean diameter. Statistics *t* shows that differences between the predicted and measured height are not significant for all inventory periods. Correla-

Trees	Year of inventory	Diameter, cm	Height, m	Bias, cm/tree	Statistics *t**	H, *t*≥1.0	Correlation between measured and predicted height per cell
		of subsample trees					
Prevailing	1998–2002	25.5	22.5	+1.4	0.00–0.47	≤5 m	0.67–0.99
	2003–2007	26.7	23.2	+0.9	0.00–0.39	≤5 m	0.63–0.99
	2008–2010	27.3	23.9	-0.3	0.00–0.88	–	0.56–0.99
	1998–2010	26.5	23.2	+0.4	0.00–0.50	≤7 m	0.65–0.98
Admixture	1998–2002	23.7	22.5	-0.8	0.00–0.25	–	0.57–0.99
	2003–2007	24.4	23.1	-1.1	0.00–0.33	–	0.61–0.98
	2008–2010	25.1	23.7	-2.7	0.00–0.16	–	0.56–0.99
	1998–2010	24.3	23.1	-2.7	0.00–0.32	–	0.59–0.98

*Statistical significance of differences with D=±2 cm, H= ±1 m

Table 3. Deviations in pine tree height as predicted by the generalized height-diameter model from that measured during various periods of forest inventory

tion between the measured and predicted height in a cell is very high; coefficient of correlation varies in the range of 0.56–0.99 both for prevailing and admixture species and in the most cases is higher than 0.7. Correlation between the measured and predicted height of trees practically does not depend on measurement period. The results of analysis of predicted height deviation from the measured one as well as correlation between the measured and predicted height of pine trees show it being possible for this analysis to transcend individual periods and use aggregate data for all the period of 1998–2010.

Analysis of correlation between the measured and predicted pine tree height in pine stands grouped by the mean diameter of stand show strong relationship between the measured and predicted height (Figure 11A).

Coefficient of correlation (R) between the measured and predicted height varies in the range of 0.88–0.94 for pine stands with mean diameter ranging from 16 to 40 cm. Analysis of relationship between the predicted and measured heights of pine trees as whole in pine stands ascertained correlation coefficient being equal to 0.97 (Figure 12A). Regression coefficient *b* in equation $h_p = b \cdot h_m$ in the most cases is equal to 0.997–0.998. Nonparametric LOESS regression analysis shows practically analogical tendencies in all the range of analyzed mean diameters of pine stands (Figure 11B). It was ascertained that there is a tendency of some overestimation of predicted height for trees in stands grouped by mean diameter in steps of 4 cm and by mean height in steps of 2 m. The predicted tree heights in the range of 6–32 m, depending on mean diameter of stands, are unbiased.

Similar results were obtained when analyzing corresponding relationship and differences between the predicted and measured height of trees of all other species in all forest stands of country. The relationship between the predicted and measured heights is defined by coefficient of correlation (*R*) that varies between 0.85 (for ash) and 0.94 (grey alder), 0.96 (black alder, oak) and 0.99 (spruce, birch, aspen, Figure 12A).

Regression coefficient *b* varies between 0.991–0.992 (for oak and grey alder) and 0.995 (for spruce, ash) and 0.997 for other four prevailing tree species like pine, birch, aspen and black alder. Nonparametric regression LOESS analysis shows negligible tendency towards underestimation of the predicted height of prevailing trees in coniferous stands with height of up to 8–12 m and overestimation of predicted heights of trees with height of over 28–30 m in stands of most species except black and grey alder whose overestimation tendency comes to sight at height of over 22

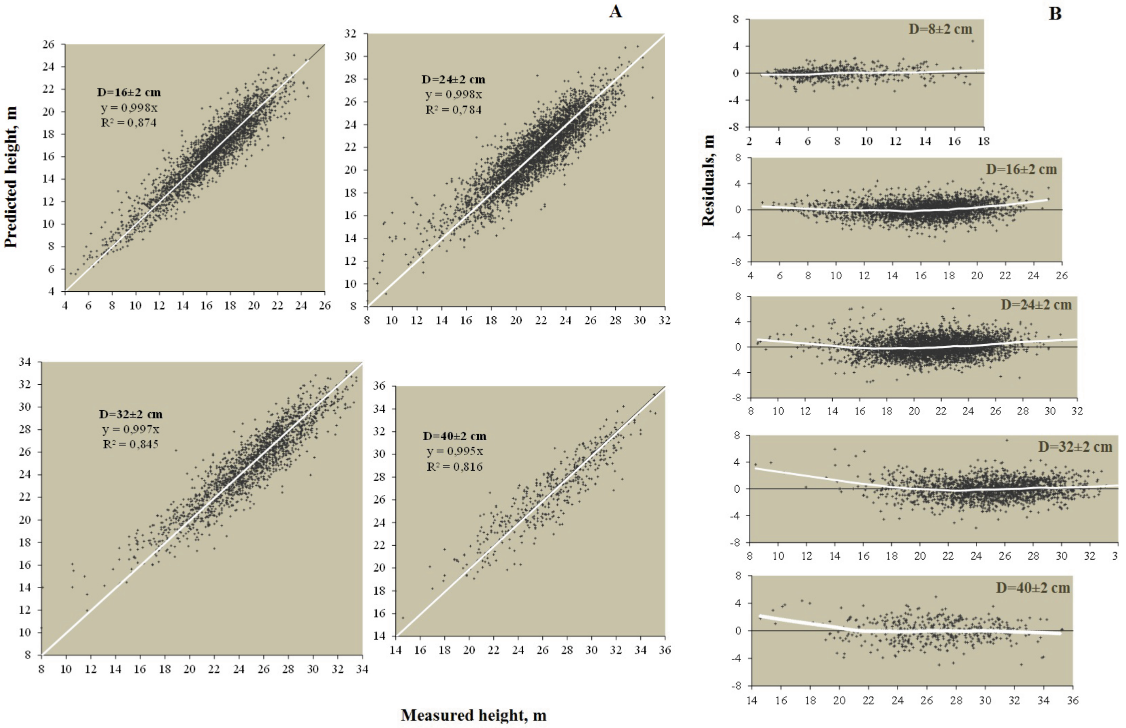

Figure 11. Analysis of deviation of prevailing pine tree height as predicted by generalized height-diameter model from that measured in pine stands with different mean diameter: A-relationship between the predicted and measured height, B-LOESS analysis

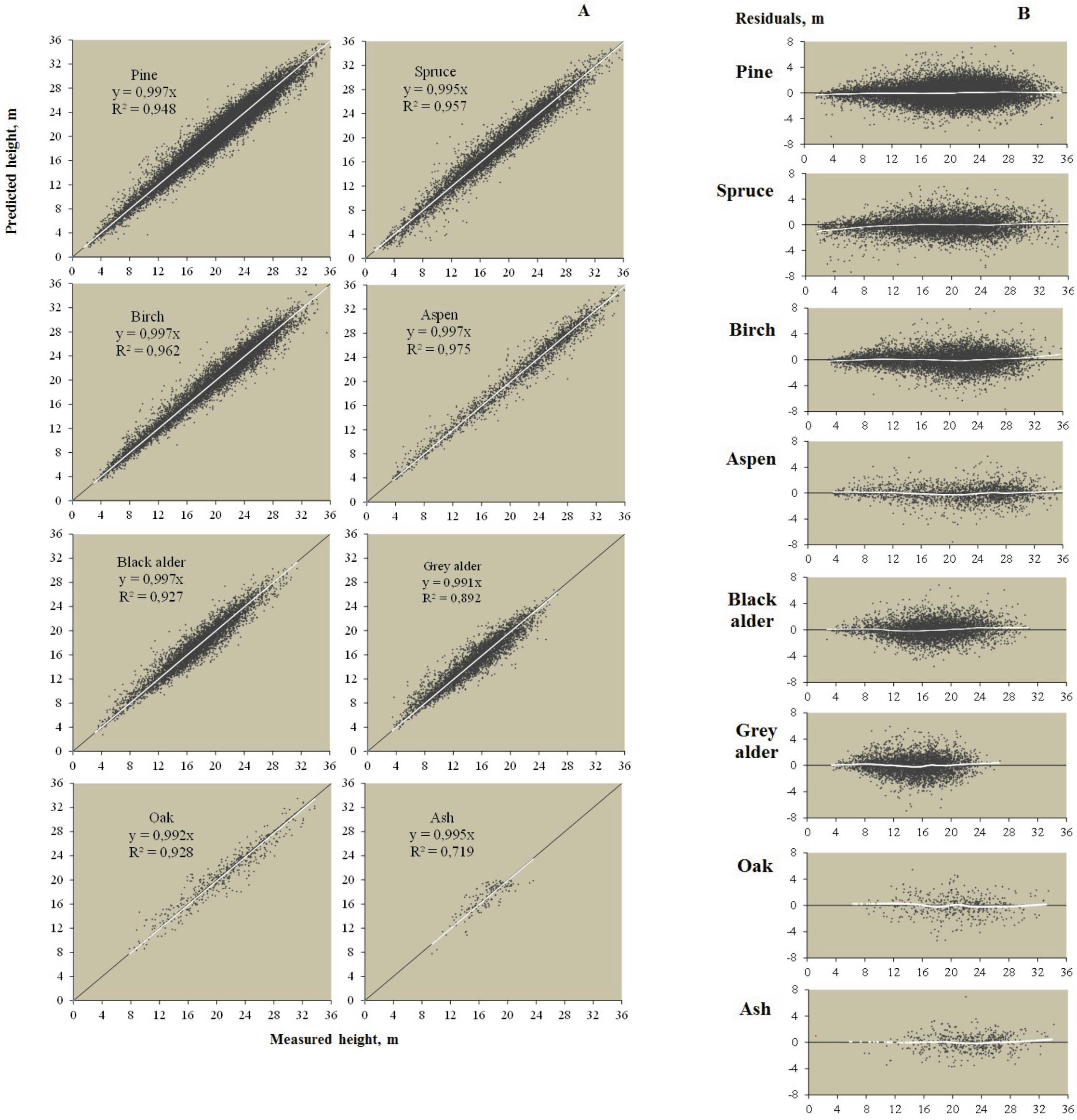

Figure 12. Analysis of deviation of prevailing tree height as predicted by generalized height diameter model from that measured in stands of different species: A-relationship between the predicted and measured heights, B-LOESS analysis

m (Figure 12B). Height underestimation of spruce stands with mean height of up to 12 m in spruce stands is more definite. This circumstance can be explained by high adaptability of spruce trees to grow in different storey or even in the understory of stand.

The mean deviation of predicted prevailing tree height from the measured one in all range of mean diameter classes varies in the range of ±1–2 cm for most species with exception of spruce (5.3 cm) and oak (4.4 cm) (Table 4). The mean deviation of height is similar for prevailing and admixture trees in stands of all tree species but often with opposite sign. (Table 4, Figure 13). The deviation of predicted height from the measured one for admixture tree species varies between –0.6 (spruce) and 4 cm (birch). The height deviation of admixture species has a tendency of shifting from negative to positive values with the increase of mean diameter of stand (Figure 13). The mean height deviation of the predicted values from measured ones for all the population independently on species is just – 0.6 cm for prevailing tree, – 2.5 cm for admixture tree and –1.3 cm on the total. Results of analysis of the predicted height deviation from the measured one show that height differences both for prevailing and admixture trees of all species are statistically insignificant at the 0.95 probability level. Student's statistic *t* in the most cases does not exceed 0.35 (0.58) value with some exception for prevailing pine and spruce trees 7 m high and admixture birch trees with height of up to 5 m (Table 4).

Table 4. Bias of tree heights predicted by the generalized height-diameter relationship model in stands of different tree species

Species		Bias, cm			Statistical significance of differences in a cell with D=±2 cm, H= ±1 m	
		all trees	trees with diameter			
			less than mean diameter	more than mean diameter	Statistics *t*	H for which *t*≥1.0
Pine	prevailing	+0.4	-19.6	+14.9	± 0.00–0.50	≤7 m
	admixture	-2.7	+8.6	-15.7	± 0.00–0.32	–
	total	-0.3	-11.9	+9.0		
Spruce	prevailing	-5.3	-5.9	-4.9	± 0.00–0.58	≤7 m
	admixture	-0.6	+0.9	-2.5	± 0.00–0.13(0.45)*	–
	total	-3.5	-2.5	-4.1		
Birch	prevailing	+0.8	-11.9	+8.9	± 0.00–0.31	–
	admixture	-4.0	+7.2	-16.4	± 0.00–0.35	<5 m
	total	-1.2	-2.5	-0.1		
Aspen	prevailing	-1.9	-5.8	+1.2	± 0.00–0.27	–
	admixture	-2.4	+6.0	-12.2	± 0.00–0.17(0.54)*	–
	total	-2.2	+0.9	-5.0		
Black alder	prevailing	+1.6	-28.0	+18.0	± 0.00–0.37	–
	admixture	-0.9	+0.3	-2.1	± 0.00–0.16(0.51)*	–
	total	+0.7	-15.7	+11.9		
Grey alder	prevailing	-1.5	+0.2	-2.4	± 0.00–0.34	–
	admixture	-3.9	+4.7	-14.3	± 0.00–0.21(0.96)*	–
	total	-2.1	+1.8	-4.6		
Oak	prevailing	-4.4	+29.9	-32.7	± 0.00–0.16	–
	admixture	-3.2	+7.4	-17.5	± 0.00–0.25	–
	total	-3.7	15.9	-25.1		
Ash	prevailing	-0.9	-8.7	+4.9	±0.00–0.17	–
	admixture	-2.4	+9.5	-23.7	± 0.00–0.18	–
	total	-1.6	1.7	-5.2		
Total	prevailing	-0.6	-13.9	+7.9		
	admixture	-2.5	+5.3	-11.6		
	total	-1.3	-5.9	+2.4		

*In parentheses – single atypical "t" values

A very important parameter of height-diameter relationship curves, especially those calculated using generalized model, is the mean diameter of stand. The mean diameter of stand divides the curve into two parts: the left, representing trees with less than mean diameter, and right, representing trees with diameter above the mean. The deviation of tree height in the left part of curve does not always compensate height deviations in the right part of the curve, especially, when the predicted height is used for stem volume estimation.

It poses the question if the height deviation is of random character in all tree diameter classes or if the deviation of the predicted height from the measured one is of systematic one. The deviation of predicted height was analyzed separately for trees with diameter below and above mean value in the stand. Results of analysis indicate that the height of pine, birch and black alder trees with diameters below the mean diameter of stand are underestimated, while that of trees with diameter exceeding the mean value of the stand is overestimated (Figure 14). Predicted oak tree height, in opposite, is overestimated if tree diameter is less than the mean stand value and underestimated for trees thicker than the mean stand diameter. Height underestimation and overestimation are symmetrical in the most cases and attain 10–20 cm (Table 4). The symmetrical deviation of predicted tree height from that measured for pine, birch, black alder and oak are usually observed at the mean diameter range above 20 cm and its values exceeds the mean height deviation up to 5–7 times (Figures 13, 14). The symmetrical deviation of predicted tree height from the measured one of spruce, aspen, grey alder and ash trees thicker or thinner than the mean stand diameter were ascertained for the mean diameter range up to 10–14 cm and are just 2–3 times bigger than the total mean height deviation. Results of this analysis suggest that it is reasonable to bring all tree species into 2 groups with different character of height deviation for trees with diameter below or above the mean diameter of the stand. Systematical predicted height deviation up to 20–40 cm was estimated for trees with diameter below to and above the mean diameter in pine, oak, birch and black alder stands, while in spruce, aspen, grey alder and ash stands this deviation had random character in average, not exceeding 5–10 cm and often changing sign. The deviation of predicted height of prevailing

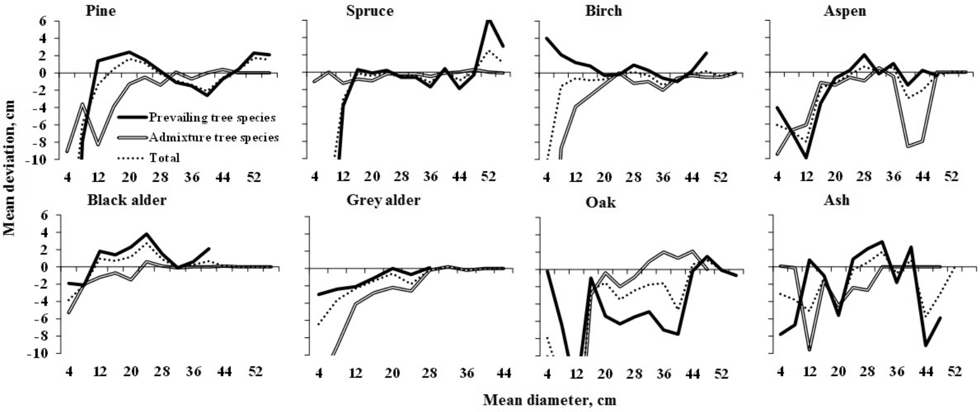

Figure 13. Mean deviation of height predicted by the generalized height-diameter model from that measured depending on mean diameter of stands as well as status of trees (prevailing or admixture) in stands of different tree species

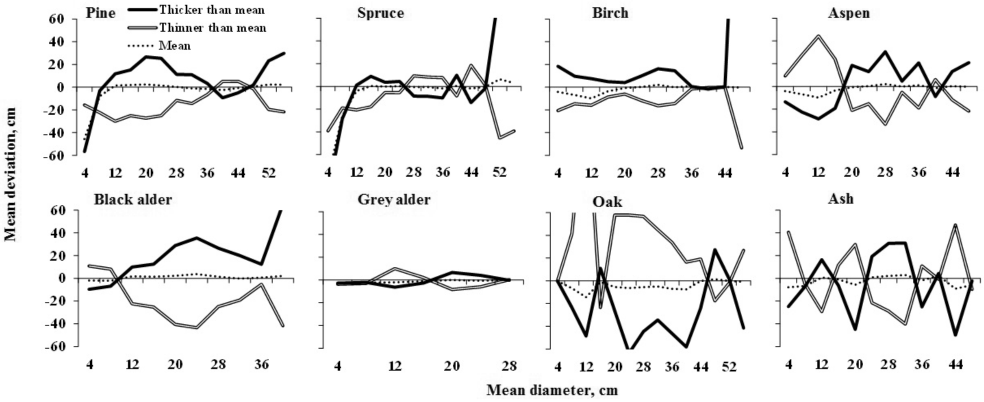

Figure 14. Mean deviation of height predicted by the generalized height-diameter model from measured one of prevailing trees below and above the mean diameter in stands of different species

pine, birch and black alder trees from the measured one suggests initiating the correction of generalized height-diameter model by implementing in Equation 1 a coefficient *k* of correction used in equation:

$$R_{Hipk} = R_{Hip}\cdot(1-k)+k. \qquad (12)$$

However, further analysis of deviation of the predicted admixture tree height from the measured one shows that the same model (1) results in deviations of different sign for prevailing and admixture trees of the species analyzed (Table 4). The total summarized deviation of the left and right parts of the diameter-height relationship curve for prevailing and admixture trees of the selected species, especially pine and birch, are just 2.5–11.9 cm. The summarized deviation of the predicted height from the measured one for all eight tree species in the left part of curve is -5.9 cm, while in the right part is +2.4 cm, i.e. only 0.1–0.2% from the mean height of trees.

Discussion

Generalized height-diameter relationship models are usually created for certain region and species, because low number of external variables makes it much easier to define common regularities of dependence between tree height and diameter. The small amount of subsample trees with measured height and diameter is usually enough to specify parameters of a generalized model and to adopt it to local stand conditions (Temesgen and Gadow 2004, Dorado et al. 2006, Sharma and Parton 2007, Trincado et al. 2007). Various techniques are employed for creation of generalized height-diameter models. The mixed-effect models are based on population–specific (considers only fixed parameters) and cluster-specific (considers both fixed and random parameters) modeling techniques. Calibration of model and adaptation it to real conditions is conducted by performing height-diameter relationship measurements on particular plot (Dorado et al. 2006, Sharma and Parton 2007, Trincado et al. 2007). Basal area, density of stand, height and diameter of dominant trees as well as site indices and geographical data are usually interpreted as fixed parameters for the generalized height diameter models (Temesgen and Gadow 2004, Dorado et al. 2006, Sharma and Parton 2007, Trincado et al. 2007). Measurements of height and diameter of one tree (Trincado et al. 2007), three smallest trees (Dorado et al. 2006) or other numbers of trees per plot (Sharma and Parton 2007) are suggested for calibration of the model.

According to results of our investigations (Кулешис 1981a, 1983b), height-diameter relationship curves in stands with specific mean diameter and mean height are affected by change of altitude and rate of height. In the generalized model elaborated for Lithuanian conditions, the mean diameter of stand was used as main factor determining the pattern of height-diameter relationship curve. This parameter is the base of every inventory and is most precisely estimated. Besides to this, it integrates influence of a lot of parameters usually participating in other generalized models, such as basal area, density, age and site growth conditions. The abovementioned parameters are highly correlated and can be expressed by the mean diameter of stand. Application of the model for tree height estimation in stands with known mean diameter growing in very different geographic regions proves acceptable for estimation of height standard deviation within the limits of ± 1.3-2.0 % (Кулешис 1983, Bruchwald, Rymer- Dudzinska 1981, Šmelko 1983, Vestjordet 1972, Товстолес 1931, Тюрин 1931, Третьяков, Горский, Самойлович 1952, Суприянович, Тетенькин, Попова 1975, Цурик 1981). Analysis of NFI height and diameter measurement data across all mean diameter and mean height range (Figure 6) shows that the curves of tree height-diameter relationship for individual stands cannot be substituted by the common curve for all mean diameter range or by other (for example, marginal) curves. That means that application of the generalized height-diameter relationship models based on the mean averaged curves in even-aged stands requires a plenty of measurements to evaluate the height-diameter relationship for individual conditions described by the mean diameter and mean height. Averaged height-diameter curves are more suited in multistory, multiple-age stands with variable size of trees (Temesgen and Gadow 2004, Кулешис 1981a, 1983b, 1992c).

Constant perfection of methods and standards applied in the forest inventory is very important in the pursuit of harmonization of the data collected to be used for national and global needs. Analysis of height tree measurements conducted by NFI of Lithuania over the period of 1998–2010 showed that the sampling design and the use of generalized height-diameter model for prediction of all tree heights by measuring small numbers of subsample trees ensures satisfactory precision. Using the model under consideration, the mean height of sample plot was estimated with mean standard error of 0.7–1.5 m. The generalized height-diameter model allows to precisely enough predict the height of trees in stands of all species. Mean deviation of the predicted height from the measured one of prevailed trees in stands of all species was -0.6 cm, while that of admixture trees was ±1–2 (4) cm. It was also noticed that thinner trees are underestimated by 5.9 cm and thicker ones are overestimated by 2.4 cm, what can lead to an overestimation of growing stock volume up to 0.1%. Bias of prevailing pine, birch and black alder tree height prediction on both sides of the mean diameter of stand is practically compensated by an opposite height prediction bias for admixture trees. A simple correction of the generalized height-diameter relationship model can improve the precision of prevailing trees' height prediction, but this would like-for-like increase height deviation of admixture trees.

Analysis of NFI data from the period of 1998–2010 confirms our previous conclusion (Кулешис 1981) about influence of the mean tree diameter in the stand on the pattern of height-diameter relations. Results of study reaffirm universality of generalized height-diameter model and, as was demonstrated earlier (Кулешис 1981a, 1992b), its applicability in broad spectrum of conditions. Results of our study shows applicability of the model for main and admixture tree species including trees of different stories and age, defined in forest stand. Our research results assembled in this paper as well as those by other authors cited in this work (Temesgen and Gadow 2004, Sharma and Parton 2007) illustrate that the relationship of height and diameter of trees as well as their standard deviation is comparable enough in even-aged stands of different species and regions, so the model proposed could serve as a base for elaborating general models for broader yet range of conditions.

Conclusions

1. Height standard deviation of stands of all the species involved varies in the range between 4.25 and 7.39 m for prevailing trees (the lowest value for alders, the upper one for aspen) and between 5.62 and 6.56 m for admixture trees.

The standard deviation of prevailing tree height in stands with mean diameter varying in the range of

±2 cm and with mean height in the range of ±1 m, varies in the range of 0.5 and 3.5 m. The highest tree height variation is observed in spruce that being followed by pine and birch stands, while the least variation is characteristic for broadleaved species stands.

2. Sampling design of Lithuanian NFI implying measurement of 1 to 8 subsample tree heights per plot allows for 0.7–1.5 m standard deviation of plot mean height estimation.

3. The generalized height-diameter model, keeping in mind different pattern of height-diameter relationship curves for stands with different mean diameter and mean height, ensures high accuracy in height prediction, its average for all stands not exceeding ±1–2 cm, which implies no real influence on the growing stock, mean stand height or estimation of site index resting on these parameters.

4. General positive evaluation of all the system (sampling design, models) used for tree height estimation during NFI still leaves the need for some improvements for pine and spruce prevailing trees less than 7 m and admixture birch trees less than 5 m high.

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ВЕРИФИКАЦИЯ МОДЕЛЕЙ ТИПОВЫХ РЯДОВ ЗАВИСИМОСТИ ВЫСОТЫ ОТ ДИАМЕТРА ДЕРЕВЬЕВ С ИСПОЛЬЗОВАНИЕМ ДАННЫХ НАЦИОНАЛЬНОЙ ВЫБОРОЧНОЙ ИНВЕНТАРИЗАЦИИ

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Резюме

Определение высоты для каждого дерева на выборочных площадках национальной инвентаризации леса (НИЛ), как правило, основывается на сочетании измерения высот и диаметров небольшого количества деревьев с регрессионными методами оценки. В НИЛ Литвы высоты измеряются для каждого седьмого систематически отобранного дерева на выборочной площадке (Kuliepis et al. 2003a, 2009b). На каждой площадке измеряются в среднем 1-7 деревьев преобладающих и 1-3 дерева сопутствующих пород. Высоты остальных деревьев оцениваются при помощи модели типовых рядов зависимости высот от диаметров деревьев (Кулешис 1981a, 1983b, 1992c), используя данные измеренных диаметров всех деревьев и соотношение между диаметром и высотой учётных деревьев. Цель данной работы – оценить точность оценки высот деревьев, используя модель типовых рядов зависимости высот от диаметров деревьев и данные измерений диаметров и высот малой выборки учётных деревьев. В работе использованы данные измеренных высот и диаметров деревьев на выборочных площадках НИЛ Литвы в 1998–2010 гг. Всего использованы данные 47500 учётных деревьев восьми преобладающих пород: сосны, ели, березы, осины, ольхи чёрной, ольхи серой, дуба и ясеня, а также 24600 учётных деревьев тех же пород, но сопутствующих в насаждениях деревьев. Отклонения оцененных с помощью модели высот деревьев от измеренных и значимость отклонений были оценены для преобладающих и сопутствующих деревьев каждой породы. Деревья ели и дуба отличаются наибольшей, а чёрной ольхи и осины – наименьшей изменчивостью высот в древостоях, сгруппированных по среднему диаметру (4 см ступени) и средней высоте (2 м ступени). Точность оценки средней высоты на выборочной площадке меняется от 3-5 % в насаждениях со средним диаметром, равным 40 см, до 5-15% в насаждениях со средним диаметром, равным 4-20 см. Среднее отклонение оцененных по модели высот деревьев от измеренных составляет -0,6 см для преобладающих в насаждении деревьев, -2,5 см – для сопутствующих деревьев и -1,3 см для всех деревьев. Различия между оцененными по модели и измеренными высотами для преобладающих и сопутствующих пород являются статистически незначимым (при уровне значимости 0,95). Выделены две группы древесных пород по характеру отклонений высот деревьев с диаметром меньше среднего диаметра древостоя и деревьев с диаметром больше среднего диаметра древостоя. Отклонения определенных по модели высот от измеренных деревьев сосны, дуба, березы и черной ольхи величиной 9-20 (33) см носит систематический характер, тогда как для ели, осины, серой ольхи и ясеня отклонения величиной 6-9 (24) см имеют случайный характер. Вся система оценки высот деревьев – схема выборки и модель типовых рядов, используемая в НИЛ Литвы, в целом является достоверным инструментом, способствующим получению данных необходимой точности, ограничиваемой точностью измерительных приборов, с минимальными затратами времени. Выявлена целесообразность усовершенствования модели типовых рядов для оценки высот преобладающих деревьев сосны и ели высотой меньше 7 м и сопутствующих деревьев тех же пород высотой меньше 5 м.

Ключевые слова: модель типовых рядов зависимости высот от диаметров, учётные деревья, оценённые по модели высоты, точность оценки