JOURNAL OF FOREST SCIENCE, *57*, 2011 (10): 409–421

Site classification vs. wood production: a case study based on Silver fir growth dynamics in the Western Carpathians

M. Bošeľa, R. Petráš, Š. Šmelko

Department of Forest Inventory and Management, National Forest Centre – Forest Research Institute in Zvolen, Zvolen, Slovakia

ABSTRACT: We analysed wood production on an example of Silver fir growth ability within site units defined in the site classification that is currently used in the Western Carpathians. It has arisen as a very important issue, since the site units have been widely used in forestry practice and, moreover, it represents one of the input variables of growth model. Research plots established for development of a yield model for Silver fir in the sixties were used. The Korf growth equation was used to model the Silver fir growth, since it showed the best fit to the data compared to other equations. The test of residual variance of the growth models and the test of regression coefficients of the growth models were employed to investigate the differences in top-height growth of Silver fir occurring on different sites. Results showed a very high variability of the top height development within the site units. Nevertheless, two main groups of sites being different from each other were recognized. But, significant differences in the height growth of fir between site units were found mainly in mature stands starting at the age of 60, which could be due to different soil depth and nutrient regime. Lastly, discussions about the approaches to site classifications all over the world showed many alternatives used to develop a classification scheme with different and in many cases unknown precision, and thus there is a need for the objectivity of classification.

Keywords: Western Carpathians; site classification; production potential; Silver fir; growth model

Sites may be classified into site types according to their similarity regarding the climate, topography, soil and vegetation. Site classification may serve a range of management purposes, including ecological stratification for optimizing the estimation of forest site productivity (Skovsgaard, Vanclay 2008). Furthermore, accurate estimates of forest productivity are needed for sustainable forest management in order to determine annual allowable cut and rotation period and to make decisions on tree species selection (Splechtna 2001). Traditional methods of mapping vegetation use the representation of stands of vegetation as discrete spatial units that belong to one of the finite number of predefined types (Brown 1998). Generally, site classification is based either on (*i*) geobotanical principles of Zürich-Montpelier School; or (*ii*) climate, relief and edaphic properties; or (*iii*) combination of characteristics of the abiotic environment and phytocoenoses. The first approach is represented by the new variant of forest typology drafted out in Russia (Zaugolnova, Morozova 2006), which looks like two-dimensional matrix, where the columns are represented by dominant tree species categories and the rows determine the subsection segregated by the ecological composition of phytocoenoses. Each subsection is analogical to association in the Z-M system (Braun-Blanquet 1964). Different variants of typological matrix for boreal, hemiboreal and nemoral botanical zone are set up according to zonal differences in tree species and understorey vegetation.

The second group of classification systems is based upon so-called ecological site classification

Support by the EU, Project No. ITMS: 26220120069 "*Centre of excelence for dicision support in forest and land*".

(ESC), which is widely used especially in Scandinavia and North America (Kuusipalo 1985; Allen 1987; Cleland et al. 1993; and others) as well as for Britain forests (e.g. Ray 2001). ESC classifies sites in terms of climatic factors and site quality, and determines the suitability of alternative tree species on the basis of interconnection of key site factors and ecological requirements of tree species.

Further, Hill (1960) proposed so-called physiographic site classification. Taking into account the terrain relief and parent rock, he divided the landscape into several site-based regions, which were further divided into smaller districts with the aim to achieve higher homogeneity. Thus, physiographic site types and forest types (characterized by both overstorey and ground vegetation) were combined to form the total site types. In Austria, Kilian et al. (1994) proposed a classification scheme, consisting of 9 main growth regions further divided into 22 eco-regions, within which 7 vegetation zones were recognized. A similar system based on 82 growth regions divided into 610 climate and geologically homogeneous growth districts was proposed for Germany by Gauer and Aldinger (2005).

In Slovakia, Blatný and Šťastný (1959) were the first who attempted to reconstruct the potential range of the original main tree species according to their occurrence recorded at present. Next, Zlatník (1959; 1976a,b) drafted a scientific concept that takes into account the relationship existing between the occurrence of native tree species and site properties. Stressing the importance of the site for phytocoenosis composition he produced an alternative approach to the generally adopted geobotanical Zurich-Montpellier school (Braun-Blanquet 1964). On the basis of research in primeval forests in the Carpathian Mountains he suggested basic site units – groups of forest site types (GFST) distinguished along the altitudinal, soil quality, and soil water supply gradients, indicated by ground vegetation in compliance with principles formulated by Ellenberg (1974, 1988). Zlatnik's School became a starting point for creating the geobotanic map of potential (original) vegetation over Slovakia (Michalko 1986) as well as the basis for further development of forest typology in Slovakia (Hančinský 1972). The basic mapping unit is forest site type defined as a group of forest biocoenoses, original or changed, and its development stages, thus the geobiocoenoses belonging to one another regarding the evolution (development) are considered. Forest site types in Slovakia have been mapped according to Hančinský (1972) methodology. However, during the decades of site survey and typological mapping the number of site units had been increasing until there were finally about 365 forest site types. Thus the need the site classification would be more suitable for forest practice led to an idea to merge forest site types into groups. Following this idea the forest site types were merged into so called management groups of forest site types regarding the site and production properties. Finally, the number of those units was 70. Nevertheless, there were several troubles because of the fact that a forest type could be located on commercial forest lands as well as on protected forest lands in extreme sites at the same time. As a consequence, the number of management groups of forest site types increased to 187.

Nowadays, growth modelling and development of growth simulators (e.g. SIBYLA – Fabrika, Slovakia) have become important in the prediction of forest development in Slovakia (Fabrika 2003) as well as in other countries (e.g. Pretzsch 1992, 2001; Pretzsch et al. 2002). Furthermore, forest site types are among the input variables to a growth model (modelling the production potential) developed in Slovakia for the Western Carpathian Mountains. Growth models developed in other countries also use the site quality estimation as an input variable. For instance, SILVA 2.2 growth model (Pretzsch 1992, 2001; Pretzsch et al. 2002) contains growth equations where the site is one of the variables to determine the growth potential (Mette et al. 2009). Thus, the knowledge of site quality and potential has been considered as very important. For instance, Assmann (1961) was convinced that well-distinguished site units could provide production homogeneity. On the contrary, Franz (1971) found height variation of 7 m, and pointed out that the main factor causing the variation was imprecise site mapping. However, no objective analyses of the tree growth or stand production potential within site units have been performed yet. There are many discussions about the accuracy of forest site classification in Slovakia (e.g. Šebeň, Bošeľa 2008) as well as in other countries (e.g. Tonteri et al. 1990).

There have been few studies focusing on the production potential of tree species within forest site units in the Western Carpathians. Thus, the objectives of this study were to obtain information about the growth potential of Silver fir (*Abies alba* Mill.) and to investigate the efficiency of several forest site units for growth and production potential estimation. Furthermore, another objective was to discuss the classification approaches all over the world and to make suggestions for an improvement of the site classification used in forestry practice in the conditions of the Western Carpathian Mountains.

MATERIAL AND METHODS

Study area

The territory of Slovakia (Fig. 1) belongs to the temperate climatic zone. The climate is determined by a great variety of climatic conditions resulting from variation in latitude, elevation and continentality. The mean annual rainfall increases from approximately 500 mm in the Danubian Lowland to about 2000 mm in the High Tatras Mts. The altitude ranges from 93 to 2,655 m a.s.l. (Gerlach Peak). The relief of Slovakia is characterized by two distinct geological and geomorphological formations: the Carpathian Arc and its adjacent lowlands. It was shaped by young tectonics, Tertiary volcanism, glacial sculpturing as well as peri-glacial, glaciofluvial and fluvial processes. Due to an extraordinary orographic variability and geological diversity of Slovakia, the Eurasian soil-geographical (horizontal) zonality vanishes in the Carpathians and the Luvisol bioclimatic region, to which Slovakia belongs, manifests itself in hilly regions. The oldest parent rocks are so called rocks of the crystalline complex (gneiss, granite, phyllite, schist and others) (Pichler 2000).

Different conditions have led to creating units which described two main gradients. Altitudinal gradient is defined by altitudinal vegetation zones. Their number is 8 and they are defined on the basis of climatic parameters and topography. The second gradient is defined by edaphic-trophic units which describe soil nutrient and soil moisture regimes, and soil depth.

Only the data belonging to the Western Carpathians were selected for our analysis.

Site and stand description

Permanent research plots (PRPs) were chosen to study the development of top heights and age on different sites. PRPs were established for a growth and yield model constructed for five main tree species in the 60's and 70's for the conditions of the Czechoslovakia (Halaj 1978; Halaj et al. 1987; Halaj, Petráš 1998). Out of all plots, the plots that are located in the Western Carpathians were selected for these analyses (Fig. 1). The

Fig. 1. Location of Slovakia and the locality of permanent research plots

plots are located on the northern side of Low Tatras (49°00'32''N and 19°24'46''E), Poľana Massif (48°36'43''N and 19°36'37''E), and Slovenské Rudohorie mountains (48°50'20''N and 20°44'06''E). The area of PRPs ranges from 0.25 to 1.00 ha. The size of the plots was determined according to the rule that 300 trees at least are needed for measurements. Such a number of trees was supposed to represent the variance and the tree distribution inside the diameter class. PRPs are located on homogeneous sites regarding the nutrient regime and climate conditions. Thus, very precise typological observations were carried out there. The forest site types (FST) (Hančinský 1972) on the plots were determined on the basis of Zlatník's typological school (Zlatník 1956, 1976a). Consequently, the FSTs were grouped into the management groups of forest site types (MGFSTs) using the climatic and soil characteristics. Thus, a total of 52 PRPs for Silver fir were chosen. In addition, measurements of trees on the PRPs were repeated 3–5 times from 1965 to 1983 in a 5–10 year interval. The age of forest stands was assessed by means of sample cores bored from 3 trees at least. The range of stand age in the year of establishment was from 30 up to 159. Out of this this number, 11 PRPs (44 measurements) occurred in management groups of forest site types (MGFST) 405 (acid beech forests in the 4th (beech) altitudinal vegetation zone), 12 PRPs (48 measurements) in MGFST 505 (acid beech-fir forests in the 5th (beech-fir) altitudinal vegetation zone), 24 PRPs (89 measurements) in MGFST 511 (fertile beech-fir forests in the 5th altitudinal vegetation zone) and 5 PRPs (20 measurements) in MGFST 516 (beech-fir forests on rocky soils in the 5th altitudinal vegetation zone). The first digit of the code refers to the altitudinal vegetation zone and the other two digits point to the soil and topography properties. In addition, the growth development was also analysed for FSTs. Thus, 11 PRPs were chosen for FST 5303 (fern fir-beech forests inferior belonging to MGFST 511), 8 PRPs for FST 4112 (hair-grass fir-beech forests with oak belonging to MGFST 405) and 7 PRPs for FST 5105 (blueberry fir-beech forests with Norway spruce belonging to MGFST 505). The distribu-

Table 1. The description of selected characteristics stratified into management groups of forest site types

	Average	Min	Max	SD
Acid beech forests in 4th AVZ (405); n = 11				
Stand age (years)	79	40	123	22
Slope inclination (°)	21	15	30	5
Altitude (m a.s.l.)	592	480	750	86
Content of silver fir (%)	90	78	99	7
Content of norway spruce (%)	5	0	16	5
Content of beech (%)	3	0	17	5
Site index of fir (m)	25	22	28	3
Acid beech-fir forests in 5th AVZ (505); n = 12				
Stand age (years)	111	47	165	33
Slope inclination (°)	20	7	27	6
Altitude (m a.s.l.)	745	560	900	135
Content of silver fir (%)	87	68	100	11
Content of norway spruce (%)	9	0	24	9
Content of beech (%)	4	0	23	7
Site index of fir (m)	27	24	30	2
Fertile beech-fir forests in 5th AVZ (511); n = 24				
Stand age (years)	95	30	174	36
Slope inclination (°)	20	15	35	4
Altitude (m a.s.l.)	754	600	960	73
Content of silver fir (%)	74	40	100	17
Content of norway spruce (%)	16	0	50	15
Content of beech (%)	8	0	36	10
Site index of fir (m)	32	22	38	4
Beech-fir forests on rocky soils in 5th AVZ (516); n = 5				
Stand age (years)	85	37	136	35
Slope inclination (°)	18	15	20	2
Altitude (m a.s.l.)	731	510	925	168
Content of silver fir (%)	91	82	99	6
Content of norway spruce (%)	8	1	16	6
Content of beech (%)	1	0	3	1
Site index of fir (m)	30	28	32	2

tion of top heights over the stand age for all site units studied in this paper is shown in Fig. 2.

Other characteristics such as altitude, slope inclination, proportion of silver fir and its site index for individual selected site units are listed in Table 1.

Height-age model

At the beginning, top-height-age development on all plots was figured to see the total variability of height growth of Silver fir. The top height was calculated as an average height of 10% of the thickest trees selected on the PRP. Moreover, top height was chosen to be analysed because the site classification by means of stand height (mainly top height) has become one of the most universal practices in forestry (Pinto et al. 2008). In addition, it is recognized as one of the most suitable indicators of site productivity (site quality) for management purposes in even-aged forest stands (e.g. Hägglund, Lundmark 1977; Monserud 1984; Schönau 1987; Rayner, Turner 1990; Rayner 1992; MacFarlane et al. 2000). In pure, even-aged stands, the height of dominant trees at a reference age (site index) is almost independent of competition (Halaj 1978; Lanner 1985; Šmelko et al. 1992). On the contrary, a few studies showed some density dependence of height growth even for dominant trees in even-aged stands (e.g. Curtis, Reukema 1970; MacFarlane et al. 2000).

Consequently, the mean curve was fitted by means of the Korf growth function (Korf, 1939) (Fig. 2) as it achieved the best fit (e.g. also in Lundqvist 1957; Zeide 1993; Liao et al. 2003). It was found to be suitable for volume as well as height growth (Šmelko 1992). Moreover, Nake (1983) considered the Korf equation as the third best one of examined growth equations. The Korf equation is sigmoid curves with asymptotes at $f(t) = 0$ and $f(t) = b_0$, and it is compared favourably to other approaches (e.g. Chapman-Richards) (Falcao 1997):

$$h_{10\%} = b_0 \exp\left(\frac{b_1}{1-b_2} t^{1-b_2}\right) \quad (1)$$

The growth equation that is supposed to sufficiently explain the growth patterns of the tree species should fulfil the assumptions of the null value – $f(t) = 0$; asymptote (maximum potential top height); and the inflexion point. In the Korf equation, the parameter b_0 defines the asymptote; b_1 and b_2 are the parameters representing the inflexion point and the shape of the curve.

In addition, we have chosen the equation with three parameters, because equations with two parameters only are more theoretical ones. Furthermore, when fit more theoretical functions – e.g. Michajlov growth function (1949, 1952), as well as the equations with four parameters – e.g. Chapman-Richards (Richards 1959), the goodness-of-fit appeared to be worse compared to the Korf equation fit. Furthermore, multiple initial values were used to ensure that the least-squares solution was the global solution, and did not fall to the local one (Zhang 1997).

All the analyses were performed by statistical software Statistica 9 (StatSoft, Inc. 2009), R, and SAS.

Comparison of height growth of Silver fir among site units

For this purpose two approaches were selected to compare the top-height growth differences among site units. As the first, we employed analysis of variance (ANOVA) and F-test to investigate if residual errors of the whole dataset would decrease when divided into the site units. The second approach was to apply t-test to study the differences in individual regression parameters among the models of site units.

(a) Comparison using the test of residual variance of growth models

F-test was employed to find out whether the top-height variability would decrease when categorized into site units. Thus, it tests the difference between two variances. In this case the variance within individual site units is compared with total variance (variance of the whole dataset) as follows:

$$F = \frac{MS_{\text{total}}}{MS_{i(\text{SU})}} \quad (2)$$

$$MS_{\text{total}} = \frac{\sum_{i=1}^{n_{\text{total}}} (y_{i(\text{total})} - \hat{y}_{\text{total}})^2}{n_{\text{total}} - k_{\text{total}}} \qquad MS_{i(\text{SU})} = \frac{\sum_{i=1}^{n} (y_{i(\text{SU})} - \hat{y}_{\text{SU}})^2}{n_{\text{SU}} - k_{\text{SU}}} \quad (3)$$

where:

n_{SU} – sample size of particular site unit,
n_{total} – sample size of the whole dataset,
k – degrees of freedom of regression parameters,
$MS_{i(\text{SU})}$ – mean square of residual errors $y_{i(\text{SU})}$ for individual site units,
MS_{total} – mean square of residual errors $y_{i(\text{total})}$ for the whole dataset.

The P-value was calculated to measure its statistical significance.

(b) Comparison using the test of regression coefficients of growth models

Student's t-test was employed to test the null hypothesis about the inexistence of differences between regression coefficients of two models:

$$t_{(df)} = \frac{b_{i(1)} - b_{i(2)}}{\mathrm{SE}(b_1 - b_2)^2} \qquad (4)$$

where:

$b_{i(1)}$, $b_{i(2)}$ – regression coefficients,

SE – standard error of regression coefficients.

However, comparing models for two datasets is usually a common problem, and there is no clear consensus for its solution (Motulsky, Ransnas 1987). It is not appropriate to use the standard error values reported by the nonlinear regression program to compare two models, as those standard error values are underestimates of the actual uncertainty. One approach is to repeat experiments several times, and to compare the resulting parameters using the t-test.

Finally, we analysed the height increment above the absolute top height as well as the age of stand to find a culmination of the height increment for different site units to ascertain the growth dynamics of Silver fir on different sites.

RESULTS

Top-height-age development of all forest stands on the PRPs was visualized to observe the total variability. It revealed really high variability in height growth (the top height at 100 years of age ranged from 25 up

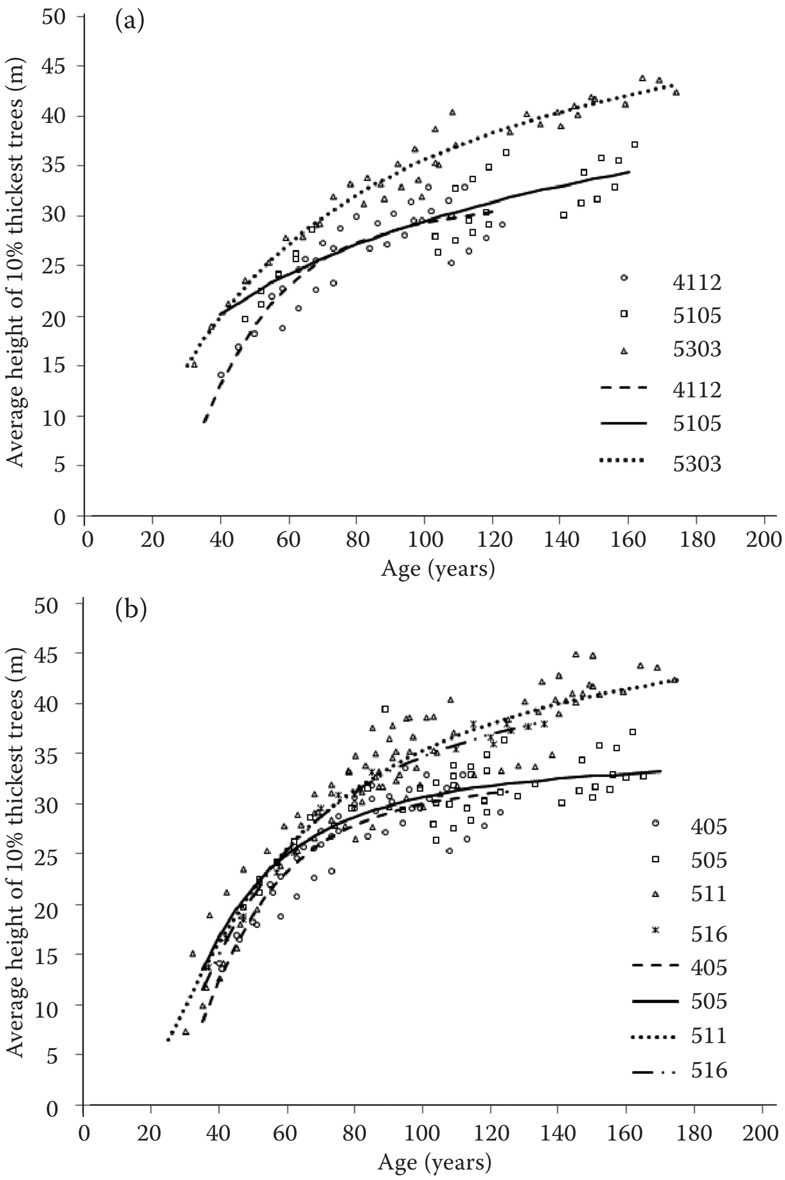

Fig. 2. Top height-age distribution and Korf model (a) for particular forest site types (FST) and (b) management groups of forest site types (MGFST)

Table 2. Regression models of $h_{10\%} = f(t)$ for forest site types (FST) and management groups of forest site types (MGFST)

	Equation	R^2	n	SE
MGFST				
405	$h_{10\%} = 32.9339 \exp[30545.9/(1 - 3.55071)\ t^{(1-3.55071)}]$	0.84	44	2.17
505	$h_{10\%} = 34.6201 \exp[1873.94/(1 - 2.94855)\ t^{(1-2.94855)}]$	0.64	48	2.07
511	$h_{10\%} = 50.4692 \exp[152.217/(1 - 2.26377)\ t^{(1-2.26377)}]$	0.89	89	2.86
516	$h_{10\%} = 44.1502 \exp[746.891/(1 - 2.63891)\ t^{(1-2.63891)}]$	0.99	20	0.77
FST				
5303	$h_{10\%} = 60.7934 \exp[16.8964/(1 - 1.79874)\ t^{(1-1.79874)}]$	0.96	38	1.36
4112	$h_{10\%} = 32.4811 \exp[14328.2/(1 - 3.38421)\ t^{(1-3.38421)}]$	0.80	32	2.18
5105	$h_{10\%} = 83.8551 \exp[1.69712/(1 - 1.33968)\ t^{(1-1.33968)}]$	0.77	28	2.36

to 40 m). Such variability is said to be the result of various factors influencing the height development.

Forest site types and management groups of forest site types (Hančinský 1972) were developed and mapped to reflect the combination of many ecological factors in the Slovakian region while they were considered to be homogeneous in the growth potential of tree species. Thus, the main goal of our study was to analyse this assumption in detail. So, the philosophy was to compare the variance within site units with total variance. For the variance computation, the differences in individual heights and model curve fit were taken. Therefore, the first step was to fit the model to the whole dataset and to calculate the total variance to be further compared to variance obtained by categorizing the dataset into site units.

In the following step, the Korf function was used to fit the empirical data within individual site units (FST, MGFST). Equations are shown in Table 2. In Fig. 2b we can notice that up to the age of around 60–70 years the top-height development seems to be very similar in all site units and we were unable to reveal any significant differences because the variability was very low. However, from this age and particularly from the age of 100 years and above, we observed great differences. Two groups of site units can be distinguished from each other there. One composed of acid beech forests (MGFST 405) and acid beech-fir forests (MGFST 505), thus it was assumed that it grows on acidic and oligotrophic soils in the 4th and 5th altitudinal vegetation zones. The other group represented fertile beech-fir forests and beech-fir forests on rocky soils making the fir species more productive.

Furthermore, the fir growth dynamics within some forest site types was studied. Those units are at the lowest hierarchical level of site classification. Thus, the sites within the units are considered to have very narrow and similar productivity of tree species naturally growing there. Nevertheless, we found some differences in growth dynamics. Comparing the models (Fig. 2a), we could recognize two main groups. The sites belonging to the first group are mesotrophic ones and the second group involves oligotrophic and acidic sites. Like in the case of management groups of forest site types, the altitudinal vegetation zones did not play an important role for the growth ability of fir. However, it is only valid when related to the 4th and 5th altitudinal vegetation zone. The growth ability of fir is likely to be different (lower or higher) in higher than the 5th or lower than the 4th altitudinal zones (due to the limiting growth conditions – moisture in lower zones and temperature in higher zones).

In the previous text, the comparison was focused on the growth dynamics in different site units only visually. Thus, in the following text, we concentrated on the statistical comparison of growth ability

Table 3. F-test of differences in variances (mean differences between empirical top height and model one) between individual site units and total

	DF	SS	MS	F	$P_{(DFi;DFtotal)}$
MGFST					
405	41	193.48	4.72	2.43	0
505	45	187.76	4.27	2.69	0
511	86	700.99	8.15	1.41	0.0239
516	17	10.2	0.6	19.14	0
FST					
5303	35	65.17	1.86	6.17	0
4112	29	137.41	4.74	2.42	0.0002
5105	25	139.26	5.57	2.06	0.0031
Total	221	2537.49	11.48		

Table 4. Regression models of $h_{10\%} = f(t)$ for new groups (oligotrophic and mesotrophic sites)

Groups of site units	Equation	R^2	n	SE
405 + 505	$h_{10\%} = 33.7551 \exp [20336.1/(1 - 3.4605)\ t^{(1 - -3.4605)}]$	0.79	92	2.36
511 + 516	$h_{10\%} = 49.6347 \exp [181.291/(1 - 2.30356)\ t^{(1 - 2.30356)}]$	0.91	109	2.58
4112 + 5105	$h_{10\%} = 36.823 \exp [360.515/(1 - 2.52507)\ t^{(1 - 2.52507)}]$	0.78	60	2.31

between individual site units (FST and MGFST). As mentioned in the methodology, F-test was employed to compare variability within the particular site units with variability in the whole dataset. As presented in Table 3, the total variability significantly decreased by applying each of the site units. This was not true of site unit (MGFST) 511 at $\alpha = 0.01$ level of significance. However, we can state that the site units selected for our study seemed to explain most of the total variability.

In addition, looking at the figures above, one could recognize two groups of sites: oligotrophic (acid) and mesotrophic. We were wondering if there were significant differences between site units belonging to the above-mentioned groups. Thus F-test was employed again. As for the MGFST, none of the units within these groups explained more variability (Table 5). Thus, with regard to the fir growth ability we could merge them. Equations for new groups (oligotrophic and mesotrophic sites) are shown in Table 4.

Similarly, we used the same procedure for the forest site types (Table 5). Also in this case, we could merge two forest site types into one group.

In the following step, we performed the same comparison by employing the *t-test*, which verified the hypothesis about the equality of regression parameters between two models that were developed for individual site units. The results are shown in Table 6. Based on these results, one could confirm the previous statement that the two main groups concerning the height growth of Silver fir can be recognized there. Sites belonging to the first group are oligotrophic (with low nutrient content and shallow soil layer) with the maximum growth ability of about 34 m at the age of 100 years. The second group consists of mesotrophic (fertile sites with deeper soil layer and sufficient moisture regime) sites, where the silver fir can reach even more than 45 m at 100 years of age. This can also be seen when the errors of the predictions are compared with one another (Tables 2 and 4). One can see that after merging the site units the prediction errors did not increase significantly.

Concerning the height growth dynamics during the whole life the culmination of height increment for the particular site units could be ordered as follows: 511, 505, 516, and 405, respectively (Fig. 3a). The highest increment at the age of increment culmination was in site units 505 and 405 and the lowest in soil unit 511. From the age of about 60 years the height increment in units 511 and 516 appeared to be higher than in the others.

DISCUSSION

On the example of silver fir growth ability we could say that the site classes created for the condi-

Table 5. F-test of a hypothesis about the equality of variances (mean differences between empirical top height and model one) between individual site units (405, 505, 511, 516, 4112 and 5105) and totals for the created new groups

MGFST	DF	SS	MS	F	$P_{(DFi;DFtotal)}$
405	41	193.48	4.72	1.22	0.2167
505	45	187.76	4.27	1.35	0.1148
Total	89	513.51	5.77		
511	86	700.99	8.15	0.81	0.8443
516	17	10.2	0.6	11.07	0
Total	106	723.89	6.64		
4112	29	137.41	4.74	1.12	0.3496
5105	25	139.26	5.57	0.96	0.5299
Total	57	319.29	5.32		

Table 6. t-test of a hypothesis about the difference in regression parameters between models

b_i	Variable	t	DF	P (two-tailed)
	405–505	0.65	90	0.5173
b_0	511–516	1.65	107	0.1019
	4112–5105	0.26	58	0.7958
	405–505	0.57	90	0.5701
b_1	511–516	1.21	107	0.2289
	4112–5105	0.37	58	0.7127
	405–505	0.29	90	0.7725
b_2	511–516	1.62	107	0.1082
	4112–5105	2.09	58	0.041

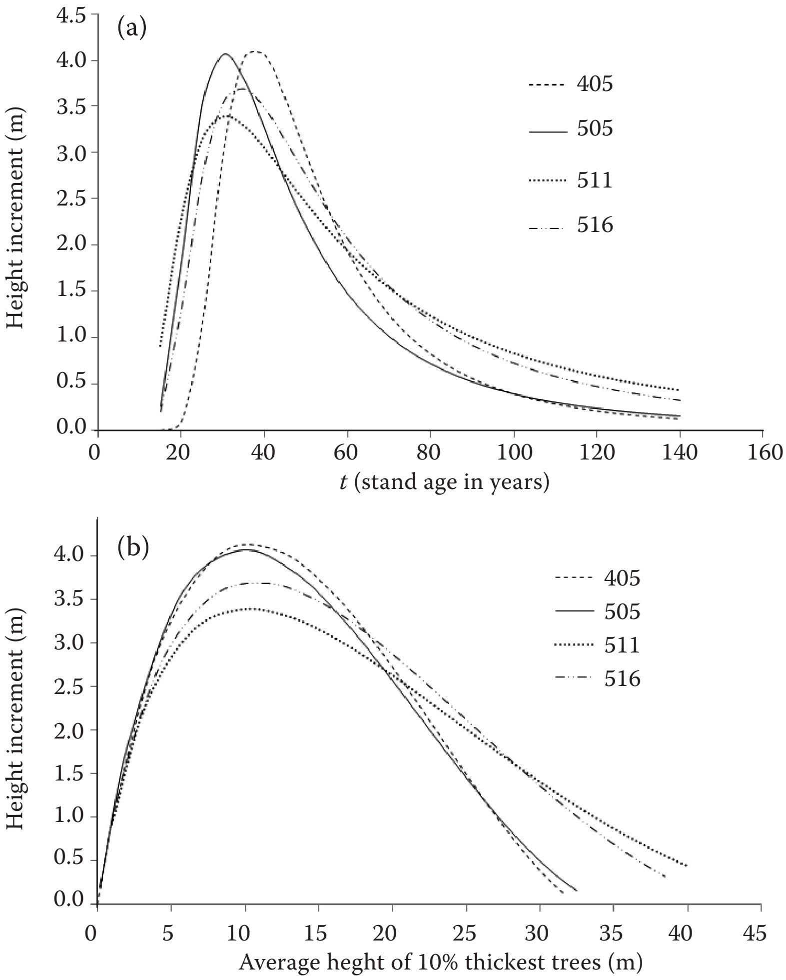

Fig. 3. Development of top height increment along (a) stand age and (b) the top height

tions of Western Carpathians do not satisfy enough when connected to timber production. It is obvious that the determination and characterization of forest site types is influenced by many factors. The determination within Zlatnik's approach is based on the types of phytocoenosis (on the basis of phytocoenological material from permanent research plots – PRPs). The forest site types are subsequently confronted with soil and other environment description. The permanent research plots in management forests are then confronted with parallel PRPs in natural or virgin (primeval) forests in order to be further reconstructed. However, the determination (analysis) of production capability within the forest site types has not been conducted yet in spite of the fact that the determination of production capability and growth development of tree species which are typical of the particular forest site types is the basic assumption for the use of forest typology and classification in management planning (Vyskot et al. 1971). In our study we found that the variability of production on the example of Silver fir growth was reasonably high, and the site index ranged from 28 to 32 in fertile beech-fir forests on rocky soils, and from 22 to 38 m in fertile beech-fir forests. Several Slovak and foreign specialists studied the wood production of forest site types. For instance in Slovakia, in their study of rotation age (maturity or exploitability) of tree species Halaj et al. (1990) revealed a high variability of production within the particular management units of forest site types, when the variability of site index within units was higher than the variability between them. Similar results were found out in our study, where in many cases the variability within a site unit was much higher than between site units.

In the site classification of Slovakian forests, the major attention during mapping was paid to the ground vegetation only. However, using the ground vegetation as an indicator of site quality has several limitations, since the vegetation composition is affected by many factors. In forest ecosystems, such factors are primarily tree layer, especially its structure and tree species composition (Križová, Ujházy 1998; Ewald 2000; Fischer et al. 2002; Bošeľa et al. 2007) and disturbance history (Bergès et al. 2006). On the other hand, Bergès et al. (2006) observed that understorey vegetation explained the same portion of variance in sessile oak site index as soil, climate and topography.

All kinds of maps (e.g. forest site type maps, soil type maps) are created with the assumption that each location can be mapped exactly to one type (Brown 1998). However, the inherent continuous nature of environmental gradients and complexity of vegetation responses ensure that obvious breaks along environmental gradients at which boundaries can easily be drawn are rare (Bryan 2006). On the contrary, management measures directed to forest stands are closely connected with the area of forest stand, so it implies the need to create spatially based categories in which similar management measures could be applied.

When we summarize the above-mentioned facts, we could conclude that the main problems and difficulties of the present site classification used in the Western Carpathians arise from (*i*) a large number of forest geobiocoenotic types and other classification units, which brings about some difficulties in their determination and identification during field works; (*ii*) the insufficiently precise reconstructive mapping of very changed forest geobiocoenoses; (*iii*) different productivity of forest stands with the same tree species composition within segments of the same forest geobiocoenotic types. The difficulties in the determination of site units are connected especially with the occurrence of the various qualitative, quantitative, topical, choric and dynamic manifestations of species (Kukla 1993b). All ecological characteristics of forest site types can be determined only indirectly at present, by means of the floristic analysis of vegetation though it is required to confront the obtained results with characteristics of the abiotic environment. The complete analysis of ecological factors influencing the nature of ecosystems has not been performed yet (Kukla 1993a).

Assuming that the classification means to break a continuum to create spatially-based categories, all the classifications are artificial (Allen 1987). Ecosystem boundaries have often been defined by consensus and thus subjectively drawn with unclear choice and weighting of input data. On the other hand, the regional ecosystem classification is important for understanding the potential distribution of species and the productivity of the landscape and it also provides a tool for interagency strategic planning (Host et al. 1996). Austin and Smith (1989) suggested that it may be more useful to accept that there is no single optimal classification, but many good classifications at a variety of scales. Therefore, it would be more accurate to include a probabilistic approach to mapping the ecosystems that would utilize continuity as an inherent status of environmental factors and vegetation responses. Many authors have dealt with the use of a fuzzy principle in various kinds of classification. For instance, McBratney and Gruijter (1992) used the principle of fuzzy logic for the classification of soils in Wespe in the Netherlands. Townsend (2000) presented a methodology for the construction of similarity index for assessing the precision of natural vegetation maps. Burrough (1989) formulated two arguments against using classical mapping units for soil types, which are further connected to forest site type mapping: (*i*) spatial variability within mapping units, and (*ii*) experimental error of measurement. Many other authors utilized fuzzy logic in development of classifications for various subjects such as forest ecology, forest management, vegetation analyses, and others (Silvert 1997; Brown 1998; Woodcock, Gopal 2000; Salski 2007; and others).

Another approach is to measure the site quality using two methods: phytocentric (direct) and geocentric (indirect) (West 2004; Skovsgaard, Vanclay 2007). The one is based on direct measurement of site index as an average height of dominant trees at a standard age. The other approach follows the relationships between site index and ecological factors (Wang, Klinka 1996; Kayahara, Klinka 1997; Corona et al. 1998; Curt et al. 2001; Seynave et al. 2005; Socha 2008) and then models for the site quality prediction are constructed directly from the ecological characteristics. From our study it is obvious that using the mean or top height of a forest stand could be one of the approaches to assess site quality.

CONCLUSION

The forest site types and their management groups were examined in connection with growth ability. Based on the site units selected for our analysis and Silver fir growth ability we could create two main groups significantly differing from each other. The first one consisted of oligotrophic (acid) sites and the second involved mesotrophic sites with quite a higher production potential. We can state that the soil conditions (nutrient status, moisture, base saturation – this is a basis for distinguishing the edaphic-trophic units, soil depth) are the main factors influencing Silver fir productivity within the 4^{th} and 5^{th} altitudinal vegetation zone in the Western Carpathians.

The present classification of forest geobiocoenoses in the Western Carpathians and in the whole Slovakian region is focused on the reconstruction of the potential vegetation which, as believed, should reflect ecological conditions of forest sites (soil and climate conditions, physiographic properties, and others) and should allow to monitor their changes. However, despite the wording of the forest site type definition (forest geobiocoenotic units), the Slovak classification is based mainly on a description of potential natural vegetation, but particularly the definitions of geobiocoenotic units do not usually contain any clear rules how field workers should cope with the current state of each particular site and forest stand on it, with man-induced changes to soil properties or tree species composition and productivity.

It can be said that the actual classification system used in the Western Carpathians (Slovakia) does not satisfy the needs of management planning, since it does not reflect the production capability of sites. Thus it would be necessary to include the production capability in order to improve the system or to propose the new one that would include the productivity of individual species. One approach would be to develop a growth model or model of potential site production capability based on the study of relationships between ecological factors and site index employing probability methods (fuzzy logic).

References

Allen, B.H. (1987): Ecological type classification for California: The Forest Service approach. General Technical Report PSW-98. Berkeley CA: Pacific Southwest Forest and Range Experiment Station, Forest service, U.S. Department of Agriculture, USA.

Assmann E. (1961): Waldertragskunde. München, Bonn, Wien, BLV Verlagsges.

Austin M.P., Smith T.M. (1989): A new model for the continuum concept. Vegetatio, ***83***: 35–47.

Bergès L., Gégout J.-C., Franc A. (2006): Can understory vegetation accurately predict site index? A comparative study using floristic and abiotic indices in sessile oak (*Quercus petraea* Liebl.) stands in northern France. Annals of Forest Science, ***63***: 31–42.

Blatný T., Šťastný T. (1959): The original vegetation of the Slovakia. Bratislava, Slovenské vydavateľstvo pôdohospodárskej literatúry: 404. (in Slovak)

Bošeľa M., Merganič J., Vladovič J. (2007): Contribution to the knowledge of the relations between structural diversity of the trees and herb layer of the forest ecosystems In: Križová E., Ujházy K. (eds): Dynamics, Stability and Diversity of the Forest Ecosystems. Zvolen, TU Zvolen: 235–240. (in Slovak with abstract in English)

Burrough P.A. (1989): Fuzzy mathematical methods for soil survey and land evaluation. Journal of Soil Science, ***40***: 477–492.

Braun-Blanquet J. (1964): Pflanzensoziologie 3. Auflage. Wien, Springer-Verlag.

Brown D.G. (1998): Classification and boundary vagueness in mapping presettlement forest types. International Journal of Geographical Information Science, ***12***: 105–129.

Bryan B.A. (2006): Synergistic techniques for better understanding and classifying the environmental structure of landscape. Environmental Management, ***37***: 126–140.

Cleland D.T., Hart J.B., Host G.E., Pregitzer K.S., Ramm C.W. (1993): Ecological Classification and Inventory System of the Huron-Mainistee National Forests. Forest Service, U.S. Department of Agriculture, USA.

Corona P., Scotti R., Tarchiani N. (1998): Relationship between environmental factors and site index in Douglas-Fir plantations in central Italy. Forest Ecology and Management, ***110***: 195–207.

Curt T., Bouchaud M., Agrech G. (2001): Predicting site index of Douglas-Fir plantations from ecological variables in the Massif Central area of France. Forest Ecology and Management, ***149***: 61–74.

Curtis R.O., Reukema D.L. (1970): Crown development and site estimates in a douglas-fiir plantation spacing test. Forest Science, ***16***: 287–301.

Ellenberg H. (1974): Zeigerwerte der Gefässpfanzen Mitteleuropas. Scripta Geobotanica, ***9***: 1–97.

Ellenberg H. (1988): Vegetation Ecology of Central Europe. 4th Ed. Cambridge, Cambridge University Press.

Ewald J. (2000): The influence of coniferous canopies on understorey vegetation and soil in mountain forests of the northern Calcareous Alps. Applied Vegetation Science, ***3***: 123–134.

Fabrika M. (2003): Virtual forest stand as a component of sophisticated forestry educational system. Journal of Forest Science, ***49***: 419–428.

Falcao A. (1997): A growth model for the National Forest of Leiria. In: Proceedings IUFRO Workshop Empirical and Process-based Models for Forest Tree and Stand Growth Simulation. 20–26 September 97, Oeiras, Portugal.

Fischer A., Linder A., Abs C., Lash P. (2002): Vegetation dynamics in Central European forest ecosystem (near-natural as well as managed) after storm events. Folia Geobotanica, ***37***: 17–32.

Franz F. (1971): Grundlagen und Verfahren standortbezogener Leistungsschätzung. München, Forstliche Forschungsberichte: 368.

Gauer H.J., Aldinger E. (2005): Forest ecologically-based nature areas in Germany. Forest growth regions and growth districts with a 1:1 000 000 map. Freiburg, Mitteilungen des Vereins für Forstliche Standortskunde und Forst-

pflanzenzüchtung. Verein für Forstliche Standortskunde und Forstpflanzenzüchtung e.V.: 43.
Halaj J. (1978): High Growth and Structure of Forest Stands. Bratislava, Veda: 282. (in Slovak)
Halaj J., Grék J., Pánek F., Petráš R., Řehák J. (1987): Growth Models of the Main Tree Species of ČSSR. Bratislava, Príroda: 362. (in Slovak)
Halaj J., Bortel J., Grék J., Mecko J., Midriak R., Petráš R., Sobocký E., Tutka J., Valtýni J. (1990): Rotation Age of Tree Species. Bratislava, Príroda: 115. (in Slovak)
Halaj J., Petráš R. (1998): Growth Models of Main Tree Species. Bratislava, Slovak Academic Press: 325. (in Slovak)
Hančinský L. (1972): Forest Types of Slovakia. Bratislava, Príroda: 307. (in Slovak)
Hägglund B., Lundmark J.E. (1977): Site index estimation by means of site properties Scots pine and Norway spruce in Sweden. Studia Forestalia Suecica, No. 138: 1–37.
Hill G.A. (1960): Regional site research. Forestry Chronicle, ***36***: 401–423.
Host G.E., Polzer P.L., Mladenoff D.J., White M.A., Crow T.R. (1996): A quantitative approach to developing regional ecosystem classifications. Ecological Applications, ***6***: 608–618.
Kayahara G.J., Klinka K. (1997): The relationship of site index to synoptic estimates of soil moisture and nutrients for western redcedar (*Thuja plicata*) in southern coastal British Columbia. Northwest Science, ***71***: 167–173.
Kilian W., Muller F., Starlinger F. (1994): The forest growth regions of Austria: a land classification based on forest ecology. Forstliche Bundesversuchsanstalt Wien (Federal Forest Research Centre). Vienna, Austria, FBVA Berichte No. 82: 60.
Korf V. (1939): The contribution to the mathematical formulation of volume in growth of forest stands. Lesnická práce, ***18***: 339–379. (in Czech)
Križová E., Ujházy K. (1998): Dynamics of mountain spruce forests in Poľana. Zeszyty naukowe Akademii Rolniczenej im H. Kolataja w Krakowie, nr 332 – sesja naukowa, ***56***: 227–241. (in Polish)
Kukla J. (1993a): The direct determination of the geobiocen edaphic-trophic orders and interorders. Ecologia (Bratislava), ***12***: 373–385.
Kukla J. (1993b): Theoretical possibilities of the direct geobiocens homeostatic trophotope determinativ. Ecologia (Bratislava), ***12***: 361–371.
Kuusipalo J. (1985): An ecological study of upland forest site classification in Southern Finland. Acta Forestalia Fennica, ***192***: 1–78.
Lanner R.M. (1985): On the insensitivity of height growth to spacing. Forest Ecology and Management, ***13***: 143–148.
Liao C.Y., Podrázsky V.V., Liu G.B. (2003): Diameter and height growth analysis for individual White Pine trees in the area of Kostelec nad Černými lesy. Journal of Forest Science, ***49***: 544–551.
Lundqvist B. (1957): On the height growth of cultivated stands of pine and spruce in Northern Sweden. Fran Statens Skogforsk band, ***47***: 1–64.
McBratney A.B., de Gruijter J.J. (1992): A continuum approach to soil classification by modified fuzzy k-means with extragrades. Journal of Soil Science, ***43***: 159–175.
MacFarlane D.W., Green E.J., Burkhart H.E. (2000): Population density influences assessment and application of site index. Canadian Journal of Forest Research, ***30***: 1472–1475.
Mette T., Albrecht A., Ammer Ch., Biber P., Kohnle U., Pretzsch H. (2009): Evaluation of the forest growth simulator SILVA on dominant trees in mature mixed Silver fir-Norway spruce stands in South-West Germany. Ecological Modelling, ***220***: 1670–1680.
Michajlov J. (1949): Matematičko formuliranje zakonot za rastenjstvo na šumskite drva i nasady – Godiš. Zborník na zemjodelsko-šumarskog fak., Skopje.
Michajlov J. (1952): Matematische Formulierung des Gesetzes für Wachstum und Zuwachs der Waldbäume und Bestände. Schweizersche Zeitschrift für Forstwesen, ***103***: 368–380.
Michalko J. (1986): Geobotanic maps of the Czechoslovak Republic. Bratislava, Veda. (in Slovak)
Monserud R.A. (1984): Height growth and site index curves for inland Douglas-fir based on stem analysis data and forest habitat type. Forest Science, ***30***: 943–965.
Motulsky H.J., Ransnas L.A. (1987): Fitting curves to data using nonlinear regression: a practical and nonmathematical review. Federation of American Societies Experimental Biology Journal, ***1***: 365–374.
Nake R. (1983): Die Eignung von Wachstumsfunktionen für die Konstruktion von Ertragstafeln. [Dissertation.] Technische Universität Dresden.
Pichler V. (2000): Natural conditions and wildlife – CST Slovakia. Available at http://www.ecosystems.sk/pages/soils.html (accessed 27 January 2011)
Pinto P.E., Gégout J.C., Hervé J.Ch., Dhôte J.F. (2008): Respective importance of ecological conditions and stand composition on *Abies alba* Mill. dominant height growth. Forest Ecology and Management, ***255***: 619–629.
Pretzsch H. (1992): Konzeption und Konstruktion von-Wuchsmodellen für Rein und Mischbestände. München, Forstliche Forschungsberichte: 115.
Pretzsch H. (2001): Modellierung des Waldwachstums. Berlin, Parey: 368.
Pretzsch H., Biber P., Dursky J. (2002): The single-tree based stand simulator SILVA: construction, application and evaluation. Forest Ecology and Management, ***162***: 3–21.
Ray D. (2001): Ecological Site Classification. A PC-based Decision Support System for British Forests. User's Guide. Edinburgh, Forestry Commission.
Rayner M.E., Turner B.J. (1990): Growth and yield modelling of Australian eucalypt forests II. Future trends. Australian Forestry ***53***: 238–247.

Rayner M.E. (1992): Evaluation of six site classifi cations for modelling timber yield of regrowth karri (*Eucalyptus diversicolor* F. Muell.). Forest Ecology and Management, ***54***: 315–336.

Richards F.J. (1959): A flexible growth function for empirical use. Journal of Experimental Botany, ***10***: 290–300.

Salski A. (2007): Fuzzy clustering of fuzzy ecological data. Ecological Informatics, ***2***: 262–269.

Seynave I., Gégout J.-C., Hervé J.-Ch., Dhôte J.-F., Drapier J., Bruno E., Dumé G. (2005): *Picea abies* site index prediction by environmental factors and understorey vegetation: a two-scale approach based on survey databases. Canadian Journal of Forest Research, ***35***: 1669–1678.

Schönau A.P.G. (1987): Problems in using vegetation or soil classification in determining forest site quality. Southern African Forestry Journal, ***141***: 13–18.

Silvert W. (1997): Ecological impact classification with fuzzy sets. Ecological Modelling, ***96***: 1–10.

Skovsgaard J.P., Vanclay J.K. (2008): Forest site productivity: a review of the evolution of dendrometric concepts for even-aged stands. Forestry, ***81***: 13–31.

Socha J. (2008): Effect of topography and geology on the site index of *Picea abies* in the West Carpathian, Poland. Scandinavian Journal of Forest Research, ***23***: 203–213.

Splechtna B.E. (2001): Height growth and site index models for Pacific silver fir in southwestern British Columbia. BC Journal of Ecosystems and Management, ***1***: 1–14.

StatSoft Inc. (2009): Statistica. Version 9.0. Available at www.statsoft.com

Šebeň V., Bošeľa M. (2008): The new approaches of forest site classification utilizing within sample-based methods focused on forest status assessing. Lesnícky časopis – Forestry Journal, ***54***: 1–16 (in Slovak).

Šmelko Š., Wenk G., Antanaitis V. (1992): Growth, structure and production of forest. Bratislava, Príroda: 342. (in Slovak)

Tonteri T., Hotanen J.-P., Kuusipalo J. (1990): The Finnish forest site type approach: ordination and classification studies of mesic forest sites in southern Finland. Vegetatio, ***87***: 85–98.

Townsend P.A. (2000): A quantitative fuzzy approach to assess mapped vegetation classifications for ecological applications. Remote Sensing of Environment, ***72***: 253–267.

Vyskot M., Doležal B., Jurča J., Korf V., Korpeľ Š., Macháč D., Polák L., Priesol A., Řehák J., Wolf J. (1971): Fundamentals of Growth and Production of Forests. Praha, SZN. (in Czech)

Wang Y., Klinka K. (1996): Use of synoptic variables in predicting white spruce site index. Forest Ecology and Management, ***80***: 95–105.

West P.W. (2004): Tree and forest measurement. Berlin, Springer.

Woodcock C.E., Gopal S. (2000): Fuzzy set theory and thematic maps: accuracy assessment and area estimation. International Journal of Geographical Information Science, ***14***: 153–172.

Zaugolnova L.B., Morozova O.V. (2006): Typology and classification of forests in European Russia: methodical approaches and their realization. Lesovedenie, ***1***: 34–48. (in Russia)

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

Zhang L. (1997): Cross-validation of non-linear growth functions for modeling tree height-diameter relationships. Annals of Botany, ***79***: 251–257.

Zlatník A. (1959): Review of the Slovak Forests According to Forest Site Type Groups. Brno, LF VŠZ. (in Czech)

Zlatník A. (1976a): Forestry Phytocoenology. Praha, SZN. (in Czech)

Zlatník A. (1976b): Review of groups of forest and shrub geobiocoen type in ČCSSR. Zprávy geografického ústavu ČSAV v Brně, ***13***: 55–64. (in Czech)

Received for publication April 1, 2011

Accepted after corrections August 24, 2011

Corresponding author:

Ing. Michal Bošeľa, National Forest Centre – Forest Research Institute Zvolen, Department of Forest Inventory and Management, T.G. Masaryka 22, 960 92 Zvolen, Slovakia

e-mail: bosela@nlcsk.org