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Allometric models for estimating aboveground biomass of young Norway spruce trees in the Western Carpathians, Slovakia

Jozef Pajtík[1], Bohdan Konôpka[1, 2]*, Vladimír Šebeň[1]

[1] *National Forest Centre – Forest Research Institute Zvolen, T. G. Masaryka 2175/22, SK – 960 01 Slovak Republic*
[2] *Czech University of Life Sciences Prague, Faculty of Forestry and Woody Sciences, Kamýcká 129, CZ – 165 21 Prague 6 – Suchdol, Czech Republic*

Abstract
In the period of climate change, it is necessary to have biomass models for trees of all sizes to make precise estimations of biomass forest stocks to quantify carbon sequestration by forest cover. Therefore, we created allometric models of aboveground biomass in young Norway spruce (*Picea abies* [L.] Karst.) trees including main components, i.e. stem, branches and needles. The models used 200 sampled trees from 10 sites located in the central part of the Western Carpathians in Slovakia. The models, i.e. allometric regression relations implemented stem base diameter (diameter d_0) and/or tree height. Moreover, using the derived allometric relations and a constant annual diameter increment of 10 mm, we calculated quasi-annual aboveground biomass production with regard to diameter d_0. While stem had the largest contribution to aboveground biomass, followed by needles and branches, a different situation was revealed for the annual aboveground biomass production with the largest share of needles followed by stem and branches. Finally, we implemented the allometric models in a specific forest stand, where repetitive measurements were performed within 14 consecutive years. The results showed for example nearly 650 kg of the aboveground biomass per 10^2 m^2 at the stand age of 10 years. The new biomass models can be applied to estimate the aboveground biomass stock in Norway spruce dominating stands in the Western Carpathians. Since the models are based on both diameter d_0 and tree height a user can choose which variable is more suitable for particular conditions.

Keywords: stem base diameter; tree height; tree components; aboveground biomass production; stand aboveground biomass stock

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1. Introduction

Norway spruce (*Picea abies* L. Karst.) is one of the most important tree species in Eurasia. Its value is related to both economic and ecological aspects together with a long tradition of its cultivation, especially in the countries of Central Europe (Ayanz et al. 2016). Under the conditions of Slovakia, Norway spruce grows at nearly 22% of forest area, and it is the second most common tree species (Moravčík et al. 2021). The species has been recently extremely damaged, prevailingly by windstorms (Bošeľa et al. 2014; Konôpka 2016). Moreover, for approx. three decades this species has been physiologically weakened by continuous intensification of extreme summer heatwaves (Konôpka & Lukac 2013; Lukasová et al. 2021) that create conditions for massive infestation of bark beetles and other pests (Kunca et al. 2015, 2019). Due to large disturbances in the present millennium, the share of young spruce stands has a continuously increasing tendency. The latest Green Report of Slovakia (Moravčík et al. 2021) for instance shows that spruce stands in the first age class (i.e. up to 10 years old) represent as much as 31% of the total spruce forest area. It means that from all tree species Norway spruce has the highest portion of stands in initial stages. That evoked to us, as forestry researchers, a necessity to pay an intensive attention to this young forest class of Norway spruce forests.

In fact, forests do not represent a passive object that is affected, mostly in negative way, by climate change. Thanks to their capability to absorb and accumulate carbon, forests mitigate the process of climate change (Waring et al. 2020). Forest destruction brings a variety of negative effects to ecosystem services including disruption of vegetation cover and related consequences to carbon sequestration. Further carbon sequestration in forest trees and soil depends on the promptness of forest

*Corresponding author. Bohdan Konopka, e-mail: bohdan.konopka@nlcsk.org
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regeneration and subsequent biomass productivity that is determined (in a very simplified way) by dividing the biomass per unit area by the age of the forest ecosystem (e.g. Lieth & Whittaker 1975). Biomass productivity and annual production can be calculated using biomass models at a tree and/or stand level (West 2009). Biomass models at a tree level are usually based on easily measurable characteristics, which are most frequently stem diameter and tree height (e.g. Satoo & Madgwick 1982).

Our literature review (e.g. Bartelink 1997; Eckmüllner 2006; Teobaldelli et al. 2009; Seidl et al. 2010; Vorster et al. 2020; Čihák & Vejpustková 2022) indicated that existing biomass models focus mostly on older developmental phases of forest trees. One of a few papers (Annighöfer et al. 2016), which concentrated on biomass models for young trees, provide generic biomass equations for aboveground biomass of nineteen forest tree species in Western Europe. Although the work also includes Norway spruce, it does not contain detailed models for individual tree components. However, the paper by Dutca et al. (2018) shows models for total tree biomass as well as for individual tree components for early growth plantations of Norway spruce in the Eastern Carpathians of Romania.

The objective of the presented work is to construct aboveground biomass models for young Norway spruce covering main tree components, i.e. needles, branches and stem. The models implemented tree size characteristics (stem diameter and/or height) as predictors. Further, we aimed at estimating annual tree aboveground biomass production with regard to tree size. This output might be used also for approximate carbon quantification, which is annually bound in forest biomass. Our regression relations would be applicable in the central part of the Western Carpathians for the sites with most frequent growth conditions for Norway spruce.

2. Material and methods

2.1. Field sampling

Under the conditions of Slovakia, Norway spruce dominated forest stands occur prevailingly between 560 and 1,350 m a.s.l. This kind of stands is found typically in the central and the northern part of the country (Fig. 1). In the mentioned regions of Slovakia, Norway spruce is indigenous to the Western Carpathians. The preliminary selection of stands was performed using the current national database of forest stands based on the data from Forest Management Plans (see also http://gis.nlcsk.org/lgis/). At the same time, the stands had to grow at moderately fertile sites; practically most of them were found on mesotrophic cambisols.

The main criteria for the selection of sampled stands were: stands originating exclusively from natural regeneration, share of Norway spruce in tree species composition at least 90%, mean stand age below 15 years. Then, we performed field surveys and selected 10 stands for further tree sampling. Our intention focused on five sub-

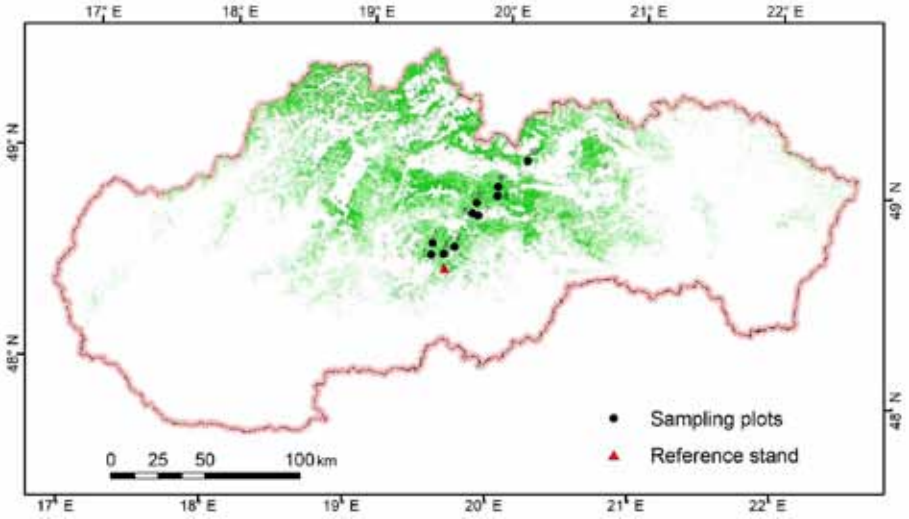


Fig. 1. Spatial distribution of sampling plots (black dots) and Norway spruce occurrence (green background) in Slovakia. The red triangle indicates the position of the reference stand where the aboveground biomass model (equation 4) was implemented.

provinces (mountains and valleys): Poľana (two plots), Slovak Ore Mts. (two plots), Horehronie Valley (two plots), Low Tatra Mts. (three plots) and High Tatra Mts. (one plot; see also Table 1). The altitudes of the selected plots were between 625 and 990 m a.s.l., mean ages of the target forest stands were from 2 to 15 years.

2.2. Tree measurements

Within the selected forest stands, totally 200 individuals of Norway spruce were subjected to our measurements. Specifically, at each site, 20 Norway spruce trees were included attempting to cover the entire height interval

present in the stand. Before cutting a tree, two stem base diameters (diameter d_0 hereinafter) were measured with a precision of 0.1 mm in perpendicular directions. Then, the tree was cut at the ground level and its height was measured with a precision of 1 cm. Then, the aboveground part of each tree was separated into braches with needles and a stem. The tree components were packed in paper bags marked with a specific site code and a tree number, and afterwards transported to a laboratory.

Each sample was stored in a dry and well-ventilated room for approximately 1 month. Within the storing period needles became dry and dropped mostly themselves, thus, it was easy to separate needles from branches. Then, each tree component, i.e. stem, branches, needles was dried under 105 °C until they reached a constant weight. The dried tree components were weighed with a precision of 0.1 g. Data on tree height, diameter d_0 and mass of tree components were used to derive allometric relations.

Table 1. Main information on site and stand characteristics.

Plot number	Sub-province unit	Soil	Altitude [m a.s.l.]	Mean stand age* [years]
1	Poľana	Cambisol	790	3
2	Poľana	Cambisol	985	5
3	Slovak Ore Mts.	Cambisol	970	11
4	Slovak Ore Mts.	Cambisol	980	14
5	Horehron Valley	Cambisol	625	4
6	Low Tatra Mts.	Cambisol	840	2
7	Horehronie Valley	Cambisol	635	7
8	Low Tatra Mts.	Podzol	820	9
9	Low Tatra Mts.	Cambisol	830	10
10	High Tatra Mts.	Podzol	990	15

*According to Forest Management Plans.

2.3. Tree biomass and production calculations

First, the relationship between diameter d_0 and tree height, including statistical characteristics, was calculated using this equation:

$$h = \frac{d_0^2}{b_0 + b_1 d_0 + b_2 d_0^2} \quad [1]$$

where
b_o, b_1 *and* b_2 are parameters, h is tree height (m) and d_0 is diameter measured at stem base (mm).

Then, models for biomass of each component, i.e. stem, braches and needles separately, as well as for the whole aboveground part together, were derived. We used three ways for biomass expression: based on diameter d_0 [see equation 2], height [eq. 3] or both d_0 and height [eq. 4]. Equations expressing specific biomass B (in kg) are:

$$B = b_0 d_0^{b_1} \quad [2]$$

$$B = b_0 h^{b_1} \quad [3]$$

$$B = b_0 d_0^{b_1} h^{b_2} \quad [4]$$

where
d_0 is a diameter at stem base, h is tree height, b_0, b_1 and b_2 are equation parameters, i are tree components (stem, branches, needles, aboveground biomass).

Annual production of stem and branches ΔB_i was calculated from models of dry biomass of woody parts B_i shown in Table 4 as a difference in mass of individual tree components in years x and $x–1$, while we assumed an annual diameter increment d_0 = 10 mm:

$$\Delta B_i = B_{i(d_0+10)} - B_{i(d_0)} \quad [5]$$

The value of the annual diameter increment of 10 mm was chosen as a uniform reference base on the base of real diameter increments of spruce in the initial developmental stages (see also Konôpka et al. 2021). Needle production was calculated differently. We used the knowledge that approximately one sixth of needle mass from the year x falls off between years x and $x–1$ (combined data from works Pajtík et al. 2013 and Konôpka 2017), i.e. according to the relationship:

$$\Delta B_i = B_{i(d_0+10)} - 5/6 B_{i(d_0)} \quad [6]$$

2.4. Implementation of biomass models at a stand level

The new biomass model [see eq. 4] was implemented for a specific Norway spruce forest stand originated exclusively from natural regeneration. The stand is located in Lipovo that is a site in the southern part of the Poľana mountains (in Fig. 1 marked as a reference stand). The altitude of the site is 980 m a.s.l., the soil is mesotrophic cambisols. In 2007, five circular plots with a radius of 2.0 m were established there. Then, diameters d_0 and tree heights of every tree located within the circular plots were annually measured (in the years 2007–2020; the stand was from 4 to 17 years old). The alometric model [eq. 4] was used to calculate the aboveground biomass at a tree level for each year. The aboveground biomass stock for each plot was calculated as a sum of the aboveground biomass values of present trees. Then, mean stand aboveground biomass stock was calculated as an average of five circular plots. Finally, the aboveground biomass stock was calculated from plot area (12.56 m^2) to an area of one are (100.00 m^2). Thinning was applied in the stand in the year 2016. Hence, the felled trees were excluded from further measurements and were not included in the aboveground biomass stock after the thinning.

All estimations were carried out using least squares methods in Statistica 7.0 /StatSoft, (Oklahoma, USA) software.

3. Results

3.1. Aboveground biomass models and production estimates

Our sampling trees had diameters d_0 between 1.5 mm and 200.5 mm, and tree heights from 0.11 m to 8.74 m (Table 2). Mean biomass of sampling trees representing stem,

Table 2. Descriptive statistics of all sampled trees of Norway spruce (n = 200 individuals).

Tree characteristics	Mean	S.D.	Minimum	Maximum	25th percentile	75th percentile	Skewness
Diameter, d_0 [mm]	36.99	41.41	1.55	200.50	8.80	52.35	1.89
Height [m]	2.08	2.05	0.11	8.74	0.54	3.05	1.30
Stem biomass [g]	1231	3,227	0.20	22,747	9.80	710.00	4.18
Branch biomass [g]	748	2,055	0.04	14,817	7.80	427.50	4.26
Needle biomass [g]	844	2,213	0.03	14,402	13.10	497.00	3.95
Aboveground biomass [g]	2,858	7,495	0.27	51,966	31.80	1,698.65	4.09

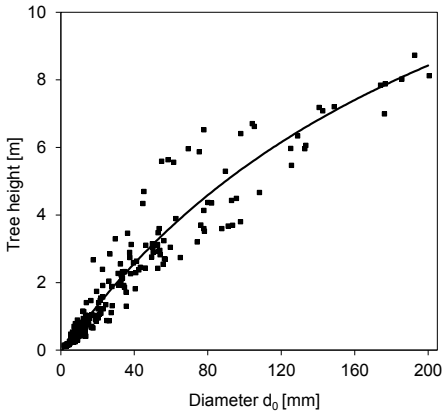


Fig. 2. Relationship between diameters d_0 and tree heights of the sampled trees of Norway spruce. Equation [1] is in the Material and method section, values of statistical characteristics are shown in Table 3.

branch, needles, and aboveground tree parts together was 1,231 g, 748 g, 844 g, and 2,858 g, respectively. The relationship between diameter d_0 and tree height was very tight (R^2 equalled 0.93; see also Fig. 2 and Table 3).

The allometric models of tree components showed very close relationships between diameter d_0 and biomass (Fig. 3, Table 4). The values of R^2 of all models were over 0.96, and the highest correlation was found for the total aboveground biomass – nearly 0.99. Tree height was also a very good predictor of tree component biomass, while the lowest value (0.81) of R^2 was found for needle biomass. The results proved that stem diameter is a better predictor of aboveground biomass than tree height. Using both predictors improved the precision of biomass models only slightly in comparison with using only diameter d_0. The fitted values of tree biomass showed that the highest values of biomass were in stem, followed by needles and branches. For instance, trees with a diameter d_0 of 80 mm had the stem, needle, and branch biomass equal to 2.10 kg, 0.82 kg, and 0.70 kg, respectively.

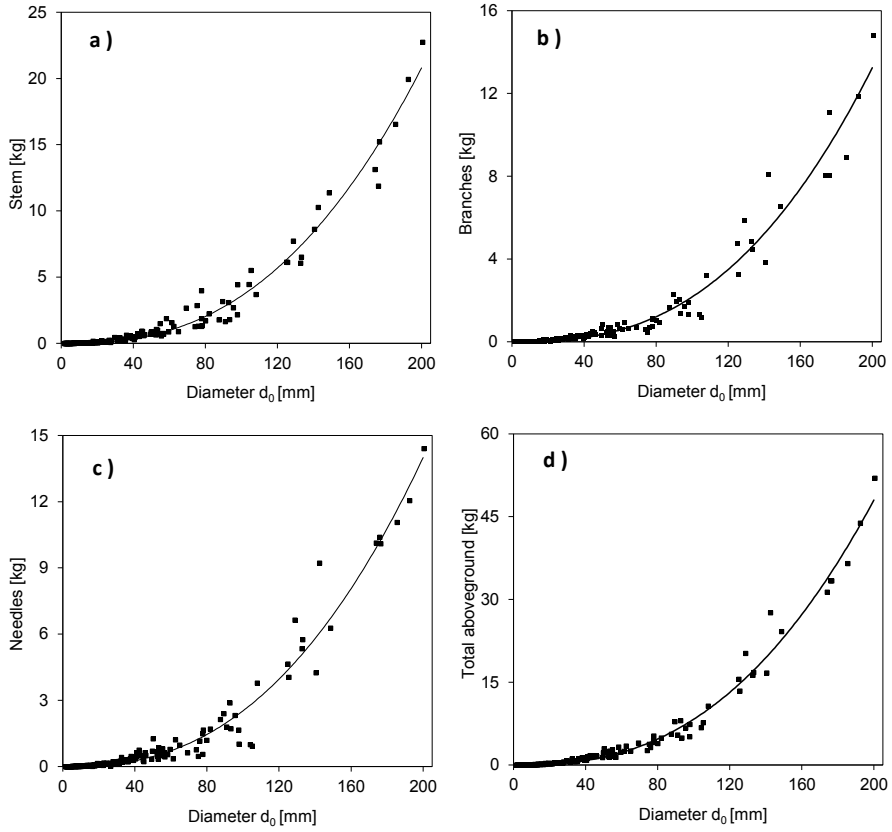


Fig. 3. Relationship between diameter d_0 and biomass of stem (a), branches (b), needles (c) and all aboveground parts together (d). Equation [2] is in the Material and method section, values of statistical characteristics are shown in Table 4.

Table 3. Statistical characteristics of equation expressing the relationship between diameter d_0 (mm) and tree height (m). The equation [1] is in the Material and methods section. Abbreviations in the table mean: b_0, b_1 and b_2 – parameters of equation, S.E. – standard error, P – p-value, R^2 – coefficient of determination, MSE – mean squared error.

Statistical characteristics	b_0	S.E.	P	b_1	S.E.	P	b_2	S.E.	P	R^2	MSE
Value	24.516	21.559	0.257	12.817	0.919	<0.001	0.054	0.006	<0.001	0.926	0.364

Table 4. Statistical characteristics of equations expressing biomass of aboveground tree components biomass using diameter d_0 (2), tree height (3), or both diameter d_0 and tree height (4) as predictors. Tree height is in m, diameter d_0 in mm, biomass is in kg. Equations [2], [3] and [4] are shown in the Material and method section. Explanation of abbreviations is in Table 2.

Equations	Component	b_0	S.E.	P	b_1	S.E.	P	b_2	S.E.	P	R^2	MSE
[2]	Stem	2.99E-05	<0.001	<0.001	2.539	0.042	<0.001				0.978	0.225
	Branches	1.30E-05	<0.001	<0.001	2.611	0,059	<0.001				0.963	0.158
	Needles	2.87E-05	<0.001	<0.001	2.472	0.051	<0.001				0.967	0.163
	Aboveground	7.05E-05	<0.001	<0.001	2.535	0.035	<0.001				0.985	0.819
[3]	Stem	3.98E-03	0.001	<0.001	3.982	0.126	<0.001				0.934	0.695
	Branches	2.46E-03	0.001	0.028	3,964	0,222	<0.001				0.820	0.763
	Needles	3.12E-03	0.001	0.028	3.884	0.223	<0.001				0.810	0.933
	Aboveground	9.40E-03	0.003	0.006	3.956	0.177	<0.001				0.878	6.864
[4]	Stem	2.25E-04	<0.001	<0.001	1.654	0.058	<0.001	1.249	0.083	<0.001	0.990	0.108
	Branches	4.66E-06	<0.001	<0.001	3.029	0.139	<0.001	−0.560	0.167	<0.001	0.965	0.149
	Needles	1.14E-05	<0.001	<0.001	2.862	0.123	<0.001	−0.536	0.147	<0.001	0.969	0.152
	Aboveground	9.73E-05	<0.001	<0.001	2.398	0.079	<0.001	0.188	0.101	0.063	0.986	0.808

On the other hand, trees with a diameter d_0 of 160 mm had 12.00 kg, 7.51 kg, and 6.91 kg of stem, needles and branches, respectively. It means that the aboveground biomass of 80 mm thick Norway spruces was more than seven times smaller than of those 160 mm thick (3.62 kg versus 26.42 kg).

As for the aboveground biomass production, needles contributed most and branches least (Fig. 4). Here, we remind that only a diameter increment of 10 mm was considered. Under this condition, trees with a diameter d_0 of 80 mm annually produced 0.71 kg, 0.65 kg, and 0.44 kg of biomass in stem, needles and branches, respectively. At the same time, annual biomass production of trees with a diameter d_0 of 160 mm was estimated to be 1.96 kg, 3.12 kg, and 1.27 kg per year in stem, needles and branches, respectively. It means that the aboveground biomass production of 80 mm thick Norway spruces was 3.5 times smaller than of those 160 mm thick (1.80 kg versus 6.35 kg per year).

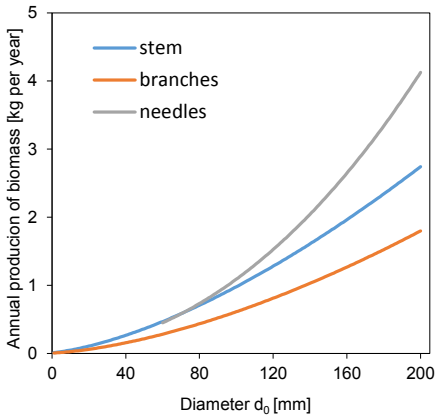


Fig. 4. Estimated annual production of aboveground biomass by tree components with regard to diameter d_0 in Norway spruce (under the condition of annual radial increment of 10 mm). Annual production of needles is shown for trees with a diameter d_0 over 60 mm. The reason is that smallest/ youngest trees might not have developed all needles of different ages (mostly from 1 year to 5 years). Thus, algorithms derived from data shown in the papers by Pajtík et al. 2013 and Konôpka 2017 might not be applicable.

Finally, contributions of single tree components to the aboveground biomass stock and production were compared (Fig. 5). Interestingly, while stem contributed most to the aboveground biomass stock, needles contributed most to the aboveground production. Branches contributed to aboveground biomass stock and production least of all components. Proportions of tree components to aboveground biomass stock and production changed with tree size (diameter d_0). The largest changes with tree size were in contributions of needles (increase) and stem (decrease) to aboveground biomass production. Fitted values suggested that in the largest trees (diameter d_0 over 170 mm), needles contributed to aboveground biomass by slightly more than 50%.

3.2. Example of biomass model implementation

Since from the specific spruce stand, we have available data on tree heights and diameters d_0 measured continuously during the last 14 years, we can implement the new biomass models in this stand. The results indicate huge temporal changes in the number of trees as well as in the mean stand diameter d_0 and tree height (Fig. 6). While in 2007 the age of the stand was 4 years, we can see a dramatic decrease of tree density at the age from 6 to 10 years. At the same time, the courses and slopes of changes in mean stand diameter d_0 and mean stand height were very similar. Aboveground biomass estimates showed that the value in a 4-year-old stand was about 208 kg per 10^2 m^2 and reached its maximum (725 kg per 10^2 m^2) at the age of 13 years before the thinning was performed

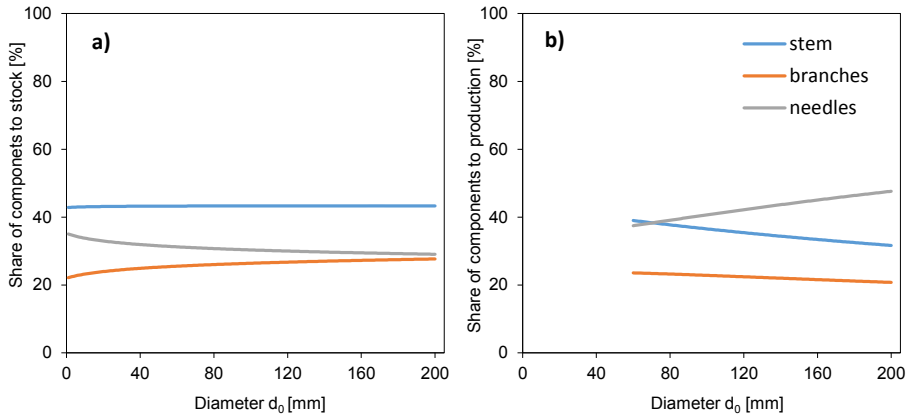


Fig. 5. Share of tree components, i.e stem, branches and needles in aboveground biomass (a), and production (b). Contribution of components to the production is shown for trees with diameter d_0 over 60 mm. The reason is explained in the caption of Fig. 4.

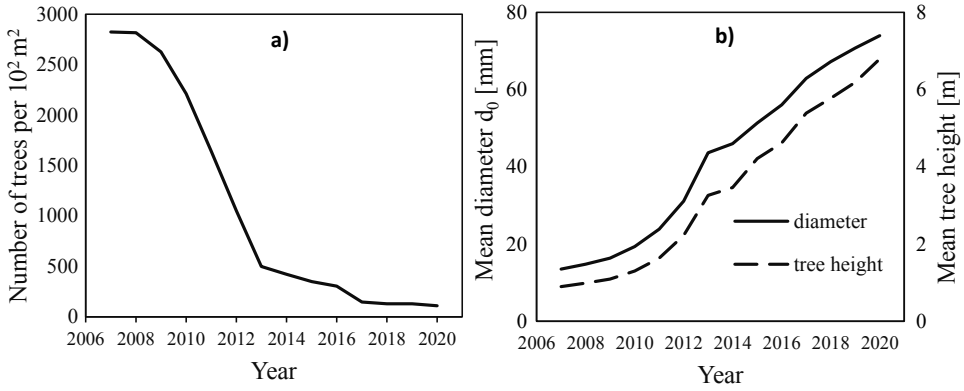


Fig. 6. Development of a number of trees per 10^2 m^2 (a) and mean diameter (b) in the reference stand in the period 2007–2020 (measured values in the stand ages from 4 to 17 years).

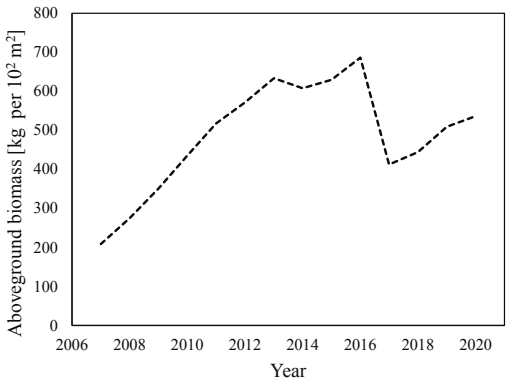


Fig. 7. Aboveground biomass stock (estimates based on model implementation) in the reference stand in the period 2007 – 2020. The decrease of the stock in 2017 was caused by performed thinning.

(Fig. 7). Then, the aboveground biomass stock fell to 444 kg per 10^2 m^2, later increasing to the value of 612 kg per 10^2 m^2 in 2020.

4. Discussion

4.1. Aboveground biomass models

The obtained results concerning allometric relations are in accordance with the previous works (e.g. Hochbichler et al. 2006; Pajtík et al. 2008) that stem diameter is the best predictor of aboveground biomass and individual components. Tree height was showed to be also suitable for the prediction of aboveground biomass, however, it was less correlated than stem diameter. Implementation of tree height, as a second independent variable in addition to stem diameter, improved the predictive power of models only negligibly. Here, we would consider also a problem of a high collinearity coefficient between these variables, which was in our case as much as 0.93. Mathematically, diameter d_0 would be the best measured variable to estimate biomass at a tree or a stand level. On the other hand, measurements of diameter d_0 can bring certain problems related to stem irregularities at the base or in the case of a repetitive survey due to the changing ground level (e.g. due to the topsoil compaction or seasonal changes in litter layer thickness). Moreover,

diameter d_0 measurements are much less comfortable for a forest surveyor than measurements of conventional diameter at breast height (diameter $d_{1.3}$). However, diameter $d_{1.3}$ is not applicable for small trees, i.e. those with a height under 1.3 m. Therefore, measurements of tree heights in young stands would be a suitable compromise between the practical performance and mathematical demands of biomass stock estimates.

The new biomass model did not include the belowground biomass. In fact, our previous results (Pajtík et al. 2008) obtained for spruce trees with a diameter d_0 of up to 70 mm showed a rather high contribution of belowground biomass to total tree biomass, and a sharp decrease with tree size. The contribution of roots stabilized to constant 16–17% for trees with diameter 60–70 mm. Therefore, we can recommend an estimation of belowground biomass to be equal to approx. 15% of the aboveground spruce biomass with a diameter d_0 between 70 and 200 mm.

Our biomass models showed that while the contribution of stem to aboveground biomass was rather stable in young spruce trees with different diameters d_0, the proportion of needles was decreasing and that of branches was increasing with the increasing diameter. These findings are in accordance with the work from Finland (Kantola & Mäkelä 2006) showing that in young Norway spruce trees the proportion of branch biomass increased and that of needle decreased with tree growth. The reason is that in very initial growth stages spruce trees had long "green" crowns (nearly to the ground level). After the canopy closure, the lack of light influences the amount of living needles more than the quantity of branches (they may die but remain attached to stems). Although our model suggested a rather stable proportion of stem in aboveground biomass, this must be accepted only in the diameter (height) range we have sampled trees for. In fact, the increasing share of stem to aboveground biomass with tree size or age (starting from a pole stage) is generally proved not only for Norway spruce and other forest tree species (e.g. Wirth et al. 2004; Repola 2009; Skovsgaard et al. 2011), but also for a large range of plant species (Poorter et al. 2011).

4.2. Aboveground biomass production estimates

As for calculations of aboveground biomass production and its structure according to components in Norway spruce, our findings should be considered with caution. We used a model diameter increment of 10 mm, which was based on measurements in four consecutive years under the conditions of one sampling plot (number 10 – High Tatra Mts.). Certainly, diameter increments vary within forest stands and are related to individual biosociological positions of trees as well as between sites, stands, climatic conditions etc. (Speer 2012). Anyway, we believe that the findings in the structure of biomass production with regard to tree components and its changes with tree size (diameter d_0) are relevant and applicable under the conditions typical for the Western Carpathians. A rather surprising finding might be the dominant contribution of needles to the aboveground biomass production and its continuous increase with tree size. Here, we should realize that Norway spruce loses annually a rather significant amount of needles that becomes a part of litter. Our previous results obtained in about 10-year-old spruce stand showed that needle litter equalled about 1/3 of the current year needle production (combined data from the papers of Pajtík et al. 2013 and Konôpka 2017). Hence, saying one specific example in a simplified way, for keeping inter-annually a constant level of all components to aboveground biomass stock (i.e. 1/3), needle production rate must be by 33% higher than those in branches and stem.

4.3. Aboveground biomass stock in a reference stand

The implementation of the new allometric models brought also stand-specific results on the aboveground biomass stock development within 14-year period (the Poľana sub-province). The maximum aboveground biomass stock (725 kg per 10^2 m^2) was estimated at the age of 13 years, then it dropped due to the performed thinning. Our previous results (Pajtík et al. 2008) for example showed the aboveground biomass stock of about 400 kg per 10^2 m^2 in a 10-year-old spruce stand in the Low Tatras. If we compare it with our reference stand, its aboveground stock was 644 kg per 10^2 m^2, i.e. about 60% higher. Lehtonen (2005) estimated the aboveground biomass stock of a 10-year-old spruce stand in southern Sweden only about 200 kg per 10^2 m^2. Biomass stock and production is not only the result of the stand age but also its genesis and especially growth conditions (site class; e.g. West 2009). Thus, our estimation on aboveground biomass stock in the reference stand is not suitable for any broad generalization. It is just an example how biomass models can be used, and also as a stand specific pattern in biomass stock development.

5. Conclusions

The new biomass models can be applied for estimating the aboveground biomass stock in Norway spruce dominating stands in the Western Carpathians. Since the models are based on both diameter d_0 and tree height, a user can choose which variable is more suitable for particular circumstances. We constructed these models to fill the gap in this field. Biomass of older stands can be estimated using Yield Tables. In Slovakia, Yield Tables provide data on spruce stand biomass stock starting from the age of approx. 15 years. However, even data

for stands over 15 years do not show the information on needle quantity and stem biomass omits the stump part.

Our estimations of aboveground biomass production should be taken with a certain level of caution, and absolute values should not be broadly generalized. Anyway, findings on certain discrepancy in contribution of tree components between the aboveground stock and production would be reliable. Higher needle contribution to aboveground biomass production than stock is logical and related to annual needle shedding. Since a tree needs to keep a balanced proportion between needles (physiologically the most active component) and woody components, it must compensate the annual needle loss by its higher production rate than of branches and a stem. Certainly, much more work in biomass production and its structure by components in Norway spruce and other forest tree species should be performed. This must consider not only tree size, but also tree age, individual tree position in a stand, and a variety of factors coming from varying abiotic conditions, i.e. soil and climate.

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