Above-ground Biomass Equations of *Populus* Hybrids in Latvia

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Abstract

The increasing use of bioenergy and therefore the expanding market for biomass have boosted interest in the establishment of short rotation plantations, where biomass could be obtained either as a production goal or as a by-product. Biomass equations are specific to species and growing conditions; however, their development takes resources and is time consuming. In the Baltic states, several *Populus* hybrids differing by a number of traits are established in small areas; therefore, interest in generalised biomass equations is increasing. The aim of our study is to develop above-ground biomass equations for the hybrid aspen (*Populus tremula* × *P. tremuloides*) and the hybrid poplar (*Populus balsamifera* × *P. laurifolia*) in Latvia and to test their robustness regarding tree age and stand density.

Sample trees were collected during the winter period in four stands located on mineral soil with normal moisture regime and similar fertility (corresponding to the *Oxalidosa* forest type) in the central part of Latvia. In total, 82 hybrid aspen trees from 12 to 19 years of age and 16 hybrid poplar trees from 62 to 64 years of age were sampled.

Differences in the above-ground biomass in both *Populus* hybrids for trees with similar dimensions were non-significant; however, a noticeable difference in biomass allocation was found. Stem biomass formed 69% and 90% of the above-ground biomass (in leaf-less state) for hybrid aspens and hybrid poplars, respectively. Present biomass equations for the hybrid aspen significantly underestimate the real above-ground biomass by 8% to 24%. All of the developed biomass estimation models were statistically significant ($p < 0.01$), and the R-squared values ranged from 0.85 to 0.96 for hybrid poplars and from 0.96 to 0.98 for hybrid aspens, suggesting good explanatory power. The developed equation based on the hybrid aspen might be applied to the hybrid poplar without significant error.

Key words: hybrid aspen, hybrid poplar, biomass allocation.

Introduction

Renewable energy is increasingly used to reduce the impact on climate (replacing fossil materials) and to ensure energy independence. The goal for the European Union is to reach 20% of the total energy consumption produced from renewable sources by 2020 (2009/28/EC), and more than half of it could be produced from biomass (Beurskens and Hekkenberg 2011). Notable areas of abandoned agricultural lands are available in the Baltic states – in Latvia, approximately 340,000 ha or ca. 11% of the total area of agricultural lands (Kviese 2013) is suitable for the establishment of short-rotation plantations of *Populus* species and their hybrids.

The first trials to study the growth of *Populus* hybrids in the Baltic States were established between the World Wars, and then in the 1960s and 1990s (Zviedris 1948, Saliņš 1971, Mangalis 1998). Research activities on hybrid aspens (*Populus tremula* × *P. tremuloides*) have been revived at the end of the previous century and the beginning of this century (Tullus et al. 2012) followed by the establishment of notable areas of new plantations, especially in Lithuania. In order to predict the potential amount of energy wood (chips) available from these plantations as well as to estimate the financial return for the owner, it is important to estimate the above-ground biomass of these plantations as well as the plantations of other hybrids. *Populus tremula* × *P. tremuloides* is the most common *Populus* hybrid in Northern Europe (Liesebach et al. 1999, Beuker 2000, Rytter and Stener 2005, Stenvall 2006, Tullus et al. 2007, Tullus et al. 2012). It occupies ca. 4,500 ha from total of ca. 5,000 ha of *Populus* plantations in this region (Rytter et al. 2013). Still, there is a lack of biomass equations for mature stands even for this hybrid, especially in Northern Europe (Hjelm and Johansson 2012). Biomass accumulation and allocation is influenced by species, hybrid, and even clones (Ketterings et al. 2001, Fang et al. 2007, Somogyi et al. 2007, Afas et al. 2008); therefore, hybrid-specific biomass equations might be needed to obtain precise estimates on the biomass of mature stands. Development of equations for every specific circumstance (site, fertility and spacing) would be unrealistically time- and resource- consuming; therefore, generalised biomass equations are a common practise. It might include trees with a wide range of diameter at breast height (DBH), height, and age, corresponding to several species and growth conditions (Wang et al. 1995, Clendenen 1996, Scarascia-Mugnozza et al. 1997, Zabek and Prescott 2006, Johansson and Karačić 2011) and might be based on several equations from different regions (Pastor et al. 1984).

Several studies have demonstrated the good fit of biomass equations developed for different ranges of stand parameters on empirical data. For instance, Johansson (2002) developed a biomass equation for *P. tremula*, based on trees with a DBH amplitude of more than 20 cm. Similarly, Wang et al. (1995) proposed a biomass equation for *P. tremuloides* with a 90-year age amplitude. Equations for poplar hybrid families grown in contrasting edaphic and climatic conditions in three sites in Europe were developed by Dillen et al. (2007). Johansson and Karačić (2011) found a model suitable to different soil conditions and locations of poplar hybrids grown in Sweden. Similarly, Rock (2007) and Afas et al. (2008) found several biomass models that might be suitable for application to another species within *Populus* genus. Moreover, Jenkins et al. (2003) developed above-ground biomass equations for groups of species merged from different genera. However, equations developed in a particular set of conditions seldom can be generalised without significant error (Ketterings et al. 2001, Zianis et al. 2005, Albaugh et al. 2009) and testing is needed to establish the limits of generalisation. To our knowledge, this is the first study concerning generalisation of biomass equations for *Populus* hybrids in the Baltic States.

The aim of our study is to develop above-ground biomass equations of the hybrid aspen (*Populus tremula* × *P. tremuloides*) and the hybrid poplar (*Populus balsamifera* × *P. laurifolia*) in Latvia and to test their robustness regarding tree age and stand density. We hypothesised that developed biomass equations might be successfully applicable within *Populus* hybrids.

Materials and Methods

Study site and sampling

Two stands of *Populus tremula* × *P. tremuloides* and two stands of *Populus balsamifera* × *P. laurifolia* growing in the central part of Latvia were studied (Figure 1). The stands are located on mineral soil with normal moisture and similar fertility (corresponding to the *Oxalidosa* forest type). The climate in the studied sites is characterised as mild with a mean monthly temperature range from ca. - 3.5 °C and ca. + 15.4 °C in January and July, respectively. Mean annual precipitation is ca. 620 mm. The highest monthly precipitation occurs in the summer months (May–September). The vegetation period usually extends from mid-April to mid-October (Klavins and Rodinov 2010).

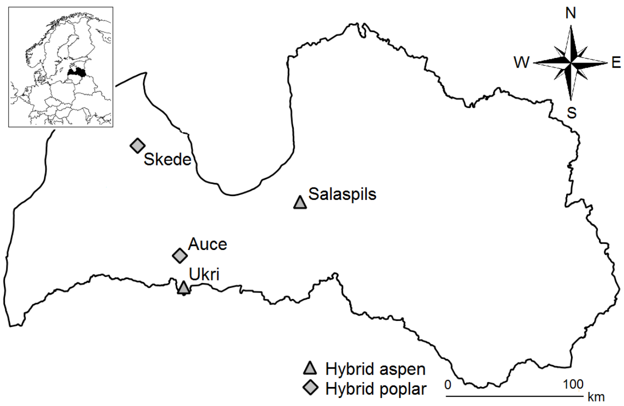

Figure 1. Location of the study sites

Parameters of selected stands are summarised in Table 1. No thinning has been carried out in the sites prior to measurements.

Table 1. Description of stands and trees used in the study

Hybrid	Location	Density, trees·ha^{-1}		N	Age	Mean of sample trees	
		Initial	Current			DBH, cm	H, m
Hybrid	Auce	5000	489	9	62	37.6 ± 3.5	26.5 ± 0.5
poplar	Skede	5000	519	15	64	40.3 ± 2.9	27.9 ± 0.7
Hybrid	Ukri	1100	898	67	12	13.9 ± 0.3	15.8 ± 0.2
aspen	Salaspils	670	442	13	19	29.5 ± 1.6	24.8 ± 0.3

N = Number of sample trees; DBH = Diameter at breast height; H = Height.

All sampling was done in the winter of 2013/2014 (November–February). Trees were felled, cut into 0.5 m long sections, and weighed. Regardless of the age of the hybrid poplar, no wood damage caused by rot was observed for the sampled trees. The living branches from each quarter of the living crown and the dead branches were separately weighed. Five sample disks (the first at 1.3 m and one more after each fifth part from the rest of the tree height) from the stem as well as four samples of branches from the mid-part of each quarter of the living crown of the trees were taken for assessment of relative humidity. In the laboratory, samples from the wood and the respective bark sections were analysed together according to standard LVS CEN/TS 14774-2.

Statistical analysis

Dry biomass of the components (stem and living branches) was calculated as a weighted average from the acquired relative humidity values and the measured weights of the respective parts (each fifth of the stem and quarter of the living crown) using the sum of the measured weight of the respective parts as weights. Very large variations both in the relative humidity and the measured biomass of dry branches were found; therefore, they were not used in further analyses to minimise the error of the estimates. Dry biomass equations were derived by linear regression models (including logarithmic, exponential, and power functions) using several independent variables: DBH, H, DBH^{-1}, H^{-1}, DBH^2, H^2, DBH*H, DBH^2*H, DBH*H^2, DBH^2*H^2, H_{lb}, L_{cr}, DBH^2*L_{cr}, where DBH is the diameter at breast height, H is the height, H_{lb} is the height of the first living branch, and L_{cr} is the length of the living crown. Intercorrelated variables (such as H, DBH, and their derivations) were not included simultaneously to avoid multicollinearity. Fit and lack-of-fit statistics were used to evaluate the regression models. Coefficient of determination (R^2), adjusted coefficient of determination (*adj.* R^2), standard error of the residuals, and Akaike information criteria were used to assess the fit to the empirical data and model quality. The normality of residuals of regression models were assessed visually and statistically using Shapiro-Wilk's normality test.

Due to similar age, dimensions, and growth conditions, both poplar stands were analysed together, but above-ground biomass models for hybrid aspens were built separately for each of the stands, differing by the tree age (12 and 19 years) and dimensions. Consequently, they were applied to the other age group and fit to the empirical data estimated. The equation based on young (12 years) hybrid aspen trees showed a good fit to the empirical data of the older trees. However, the generalised equation showed the best fit if the small and large trees were pooled. Empirical data of hybrid aspens were used to test the fit of already published biomass equations for the hybrid aspen and both of its parental species (Table 2). All tested equations contained DBH as an independent variable, and DBH ranged from the original data covering 66.2%, 82.3%, and 100% of DBH of the sampled trees. A *t*-test was used to assess the differences in the mean biomass between ages, hybrids, and estimates of equations. Pearson's correlation coefficient was used as a measure of linear dependence between empirical values and estimates of acquired models. Statistical analyses were performed using R 3.0.2 (R Core Team 2013).

trees with like dimensions (D ranged 19.0 cm–37.9 cm, H ranged 18.0 m–30.1 m; Figure 2). A noticeable difference in biomass allocation was found. The stem formed 69% of the above-ground biomass for the hybrid aspen, while for the hybrid poplar, it exceeded 90% (Figure 2). The proportion of stem when comparing the hybrid aspen stands with spacing 3 □ 3 and 3 5 m was 77% and 70%, respectively (data not shown). Larger trees of both hybrids tended to allocate higher proportions of biomass in branches (Figure 3).

All the provided models as well as their coefficient estimates were statistically significant ($P < 0.01$, Table 3). For

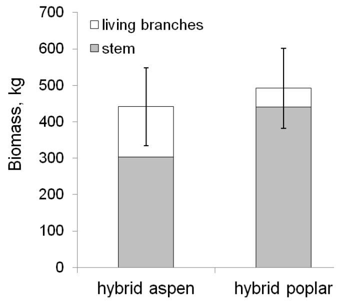

Figure 2. Differences in above-ground biomass for trees with similar diameter (range 19.0 cm– 37.9 cm) and height (range 18.0 m–30.1 m). Error bars represent 95% confidence intervals

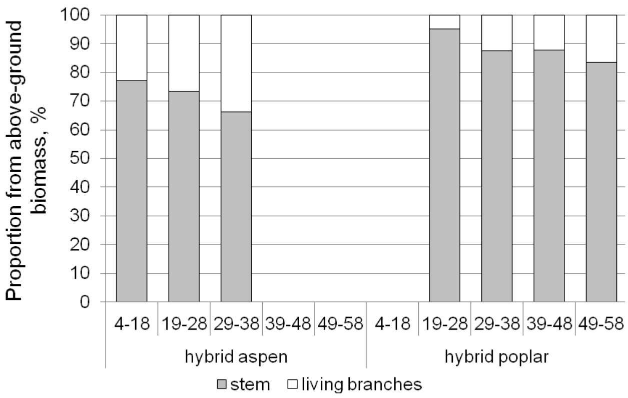

Figure 3. Biomass allocation according to diameter groups (cm) for the hybrid aspen and the hybrid poplar

Table 2. Biomass equations used to test the fit to empirical data

Reference	Function	a	b	R^2	DBH range, cm	Species
Rock (2007)	$W=a*D^b$	0.0519	2.545	0.941	13.2-33.0	*P. tremula* × *P. tremuloides*
Johansson (2002)	$W=a*e^{(b*D)}$	8.143108	0.012749	0.95	11.0-35.6	*P. tremula*
Pastor et al. (1984)	$W=e^a*D^b$	4.4564	2.4486	0.992	1.0-39.6	*P. tremuloides*

DBH = Diameter at breast height.

Results

Mean above-ground biomass of hybrids in leafless state reached 56.9 ± 6.5 kg, 422.1 ± 104.0 kg, and 893.9 ± 198.8 kg per tree for 12- and 19-year-old hybrid aspen and hybrid poplar trees (62-64 years), respectively. However, regardless of the uneven age, both *Populus* hybrids had similar biomass for

the hybrid aspen, the best models for estimation of dry biomass of the stem and the total above-ground biomass were linear models with DBH^2*H as an independent variable. The mean biomass of 19-year-old trees, estimated with the equation acquired from the 12-year-old trees, was similar to the empirical data ($P = 0.85$), and the gradient of the regression line was very close to that of the equation acquired from the 19-year-old trees (Figure 4, Table 4). In contrast, the biomass equation acquired from the 19-year-old trees significantly ($P < 0.01$) underestimated the mean biomass of 12-year-old (smaller dimension) trees (Figure 5). If estimates of stem biomass were compared, the equation acquired from 19-year-old trees significantly ($P < 0.01$) overestimated the stem biomass of younger trees. Equations based on above-ground biomass data from both stands together showed the best fit for smaller and larger trees with acceptable (2.7%–4.2%) deviation in the mid classes (Table 4). The biomass of hybrid aspen branches was best described by the power equation of the DBH (Table 3).

Strong evidence of a linear relationship between DBH (also DBH^2*H) and stem biomass was found for the hybrid poplar; however, the residual statistics showed deviations from the linear model assumptions. Therefore, the best model for estimation of dry stem biomass was a power regression model, using DBH as an independent variable (Table 3), which showed just slightly worse results in the fit and lack-of-fit statistics, but was noticeably improved in the residual statistics. In the case of the dry biomass of living branches, three outliers that had Cook's distance > 0.5 were excluded for the hybrid poplar; thus, the statistical properties of the equations improved. Still, all the models violated the as-

Table 3. Summary of the acquired equations

Hybrid	Biomass component	Equation	Independent variable	a	b	R^2	N	DBH range, cm	H range, m
Hybrid aspen	ABL	$m=a+bx$	DBH^2*H, m^3	-2.173	189.372	0.98	62	9–37	10.8-27
Hybrid aspen	ST	$m=a+bx$	DBH^2*H, m^3	5.752	126.246	0.98	76	9–37	10.8-27
Hybrid aspen	LB	$m=ax^b$	DBH, mm	0	3.074	0.96	63	9–37	10.8-27
Hybrid poplar	ST	$m=ax^b$	DBH, m	3886	1.778	0.96	24	23–57	22.49-31.70
Hybrid poplar	LB	$m=a+bx$	DBH^2L_{cr}, m^3	-17.2	58.66	0.85	21	23–57	22.49-30.60
Hybrid poplar	ABL	$m=ax^b$	DBH, m	5148.91	1.9367	0.96	24	23–57	22.49-31.70

N = Number of trees; DBH = Diameter at breast height; H = Height; ST = Stem; LB = Living branches; ABL = Aboveground living; L_{cr} = Length of the crown.

Table 4. Differences between real (empirical values) and estimated (equations) above-ground biomass of the hybrid aspen

Equation	DBH range, cm						
	9.0–13.9	14.0–18.9	19.0–23.9	24.0–28.9	29.0–33.9	34.0–38.9	9.0–38.9 (total)
Based on 12-year-old trees	4.6 %	-0.2 %	1.5 %	2.8 %	1.1 %	-0.9 %	2.3 %
Based on 19-year-old trees	-12.2 %	-7.3 %	1.2 %	3.8 %	2.7 %	0.8 %	-7.6 %
Based on all trees	3.2 %	-0.2 %	2.7 %	4.2 %	2.6 %	0.6 %	1.9 %

DBH = Diameter at breast height.

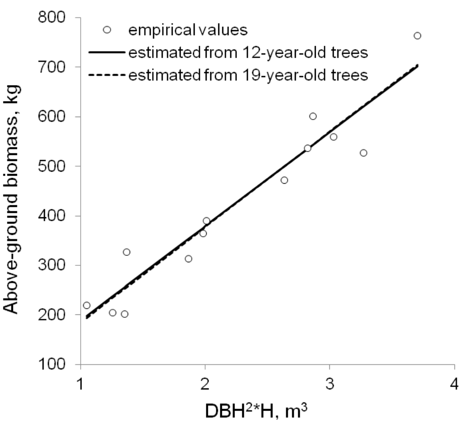

Figure 4. Above-ground biomass of 19-year-old hybrid aspens

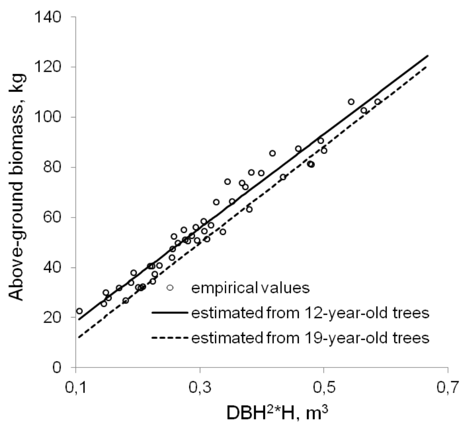

Figure 5. Above-ground biomass of 12-year-old hybrid aspens

sumption of constant error variance. Nevertheless, the best model was a linear equation using DBH^2*L_{cr} as an independent variable (Table 3). Despite variability in the dry biomass of living branches, the relationship of total dry above-ground biomass was similar to that of the stem. The power regression model using DBH as the independent variable was the best model in each step of the evaluation.

Equations developed for the hybrid aspen worked quite well for the hybrid poplar, and no significant differences were found for the mean above-ground biomass of the hybrid poplar between empirical and estimated values with the equation of the hybrid aspen ($P = 0.71$, Figure 6). However, when the equation developed for the hybrid poplar for the above-ground biomass was applied to the hybrid aspen, the result was overestimated (Figure 6). When only trees with similar dimensions (DBH = 23 cm–36 cm; 12 trees from each hybrid) were selected, the total above-ground biomass of hybrids was similar (P-value > 0.05, Figure 2).

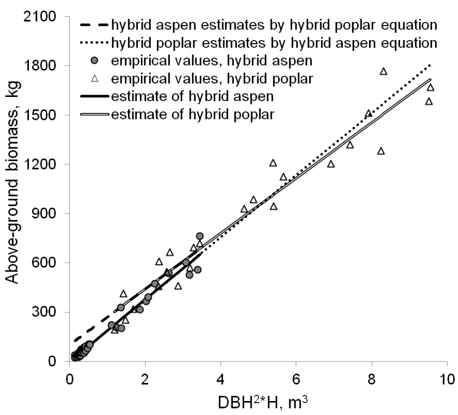

Figure 6. Fit of biomass equations of the hybrid aspen and the hybrid poplar

None of the previously published equations fit our hybrid aspen data (Figure 7). The equation by Rock (2007) significantly underestimated the biomass in all DBH ranges ($P < 0.01$) by 24% on average. In addition, the equation by Pastor et al. (1984) underestimated it significantly ($P < 0.01$); however, the difference was observed mainly for the largest trees (DBH > 18 cm), where the biomass was underestimated by 14%. Values obtained from the equation by Johansson (2002) did not differ significantly from the empirical ones ($P = 0.77$). However, this estimate deviated from the real values noticeably (Figure 7), underestimating the biomass by 8% in total, while overestimating the biomass of larger trees (> 32 cm) by 24%.

Discussion and Conclusions

The living crown components have been reported to have high variation, in comparison to stem and whole tree

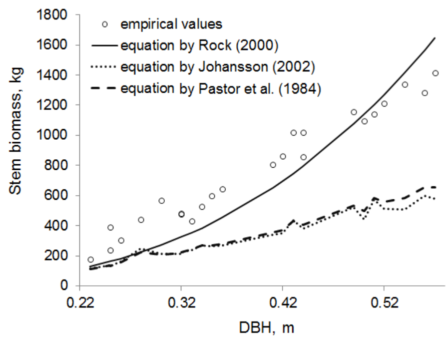

Figure 7. Accuracy of existing equations (Table 2) to predict the above-ground biomass of the hybrid aspen

biomass (Johnstone and Peterson 1980), as confirmed by our study. Therefore, the equation for the estimation of dry biomass of living branches should be used cautiously. The great variability in the dry biomass of living branches could be explained by the weaker relation to tree DBH compared to the diameter at the crown base (Johnstone and Peterson 1980) and the local conditions (i.e., competition index) (Wang et al. 2002, Zabek and Prescott 2006), affecting both the amount of branches produced as well as their diameters and, consequently, time of death. However, none of the least characteristics can be readily measured, and thus are not likely to be applied in practise.

The proportion of stem and total above-ground biomass of the hybrid aspen in Latvia was similar to that reported in Sweden (83%–85% at the age of 25 years) and Estonia (58%–86%, mean 73%) (Rytter 2006, Tullus et al. 2009). Similarly, the smallest hybrid poplars (DBH 19 cm–28 cm) had significantly higher proportions of stem biomass than the largest (DBH 49 cm–58 cm) at 95% and 83%, respectively (Figure 3). The proportion of the stem from the biomass of a tree for the hybrid poplar was slightly higher in our study than the range of values reported from 41 stands at the mean age of 20 years (oldest: 73 years, second-oldest: 41 years) in Sweden, where the stem accounted for 51% to 90%, with a mean value of 75%, from the total biomass (with leaves) (Johansson and Karačić 2011). However, the biomass of the stem and branches might be inversely and compensatorily related (Bickelhaupt et al. 1973), thus resulting in a similar above-ground biomass, which is different in its allocation, as also shown in our study of trees of both hybrids with similar dimensions (Figure 2).

Genotype has a major influence on crown architecture (Ceulemans et al. 1990), and the hybrid aspen showed a higher share of branches than the hybrid poplar. Similarly, differences in biomass allocation between *Populus* hybrids have been found in studies by Wu and Stettler (1998) and Wullschleger et al. (2005). Alternatively, the age of the trees might play a role. The proportion of branches decreases as a stand ages (Wang et al. 2002), and a noticeable contrast in the age of the hybrid aspen and the hybrid poplar might be the reason for differences in the stem-to-branches ratio for trees with the same dimensions (Figure 2). Moreover, wood density increases with age (Yanchuk et al. 1983, Yanchuk et al. 1984, Fang et al. 2004), suggesting higher biomass for older trees of the same size (Figure 2).

The proportion of branches was related to the size of the tree; both hybrids showed increasing proportions of branches for trees with larger DBH (Figure 3), in contrast to the results reported by Tullus et al. (2009) for young (7-year-old) hybrid aspens. A rapid increase in the proportion of living branches was observed from the DBH group 19 cm–28 cm to 29 cm–38 cm (Figure 3) that suits other studies (Johansson 2002, Wang et al. 2002, Zabek and Prescott 2006). Trees grown in higher densities allocate higher proportions of biomass in the stem (DeBell et al. 1996, Karačić 2005, Fang et al. 2007, Christersson 2010); therefore, it might be the reason for the above-ground biomass underestimation of 12-year-old hybrid aspen trees, when the equation developed for older trees was applied (Figure 4). Thus, biomass equations based on older trees calculate more weight on the proportion of stem, resulting in an underestimation of the total above-ground biomass.

In contrast, the equation based on young (12 years) hybrid aspen trees showed a good fit to the empirical data of older trees (Figure 5). Similarly, Pastor et al. (1984) found more accurate predictions based on equations developed for smaller trees. However, the small sample size used to develop the biomass equations might be the cause for the bias, thus generalised equations might provide more reliable results (Clendenen 1996), as confirmed in our study (Table 4).

Biomass equations based on hybrid aspen trees showed good fit to the empirical data of the hybrid poplar (Figure 6). In contrast, the equation for the hybrid poplar overestimated the biomass when applied to the empirical data of the hybrid aspen (Figure 6). The medium and large trees contribute most in the development of biomass equations in old stands (Wang et al. 2002), and this effect is specially facilitated by the power form of DBH as an independent variable. Thus, the equation was less precise in the estimation of small trees conforming to dimensions of the hybrid aspen. Use of the independent variable DBH^2*H provides more reliable results for stem biomass than most commonly used DBH, since it represents volume (Freedman et al. 1982). However, the tree height obtained is closely related to DBH, thus non-significantly affecting the precision of estimates (Niklas 1994), and all applied equations contain DBH as the only variable (Table 2). Nonlinear functions used in the equation by Rock (2007) and Pastor et al. (1984) are strongly determined by medium and large sample trees (Wang et al. 2002), which also contained larger proportions of branches (Figure 3). Thus, the application of these equations to data with a linear structure resulted in underestimation. In contrast, the equation by Johansson (2002) underestimated small and medium trees and substantially overestimated the biomass of large trees, most probably due to its exponential form. In contrast to our results (Figure 7), in the study by Rock (2007), equations by Johansson (2002) and Pastor et al. (1984) and equations based on his empirical data (Equation 1 in this study) overestimated the total above-ground biomass.

The study resulted in equations describing the above-ground biomass of the hybrid aspen (*Populus tremula* × *P. tremuloides*) and the hybrid poplar (*Populus balsamifera* × *P. laurifolia*) in Latvia. Our hypothesis was partly confirmed, and the equation based on the hybrid aspen might be applied to the hybrid poplar without significant error. However, they cannot be applied *vice versa*.

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