Above-ground Biomass Models of 40-year-old Norway Spruce in Latvia

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Abstract

The importance of wood biomass as a source of bioenergy at wider scales, i.e. for a centralized production of heat and electricity, is increasing. Hence, precise estimates of biomass are necessary for the calculation of available resources and carbon budget. Mathematical models based on easily measurable variables can notably facilitate the estimation of biomass of trees. However, such models are usually locally (regionally) applicable. The biomass of the aboveground parts (stems and branches and total) and the dimensions were measured for 29 Norway spruce (*Picea abies* (L.) Karst.) trees at the age of 40 years, representing the eastern part of Latvia. Different linear models were fitted to the biomass data; tree height (H), stem diameter at 1.3 m height (D) and their combinations were used as the independent variables. The estimates of stem biomass and their mean relative errors were compared between the best of the developed models, traditionally used derivatives of wood volume tables and models developed for Finland by J. Repola (2009).

A linear model with D and H as two independent variables showed the best fit to the biomass of stem; the power model with D^2H as the independent variable performed best for the total aboveground biomass; the branch biomass was best predicted by the power model based on D. The mean relative errors of the stem and total aboveground biomass was *ca* 8%, while the model of branch biomass had higher relative error, *ca* 20%. The estimates of stem biomass by the traditionally used volume tables and the developed models did not differ significantly, but the relative errors were lower for the developed model. However, the relative errors of the stem biomass estimated by the volume tables were correlated with D, suggesting systematic bias. The developed models performed better than those established in Finland, which underestimated stem and branch biomass, but overestimated the total aboveground biomass and had significantly higher relative errors of the estimates.

Key words: *Picea abies*, aboveground biomass, biomass estimation, allometric equations, tree dimensions, hemiboreal forest zone.

Introduction

With the increasing use of biomass as a source of renewable energy (Dhillon and Wuehlisch 2013, Schueler et al. 2013), as imposed by the obligations of the national policies and the international treaties (e.g. EU Directive 2009/28/EC of 23 April 2009) and growing importance of the assessment of national carbon budgets (Haughton 2005, Brandao et al. 2013), a precise estimation of biomass resources is necessary (Keith et al. 2009, Pan et al. 2011). Hence, the development of a simple and precise methodology (Petersson et al. 2012) is crucial for the estimation of carbon stock. The information on tree biomass is also important in the practical forestry for the assessment of available energy resources, as well as for research purposes, e.g. estimates of nutrient cycling and carbon fluxes (Schroeder et al. 1997, Pregitzer and Euskirchen 2004).

The direct measurements of biomass of tree, which are the main producers of organic matter in forest ecosystems, are time and resource consuming. For this reason, different biomass models based on easily measurable variables of tree have been developed (Ter-Mikaelian and Korzhukin 1997, Lambert et al. 2005, Mikšys et al. 2007, Repola 2009). In the Nordic countries, where the forest ecosystems have a major role in biomass production and hence in national economics (Hultkrantz 1992, Adamowicz et al. 1996), several models for the estimation of tree biomass have been produced for the most common tree species – Scots pine, Norway spruce and silver birch (Classon et al. 2001, Lehtonen et al. 2004, Wirth et al. 2004, Zianis et al. 2005, Mikšys et al. 2007, Pajtik et al. 2008, Repola 2009). These studies showed that a high precision of biomass estimates of different tree components (i.e. stem, branches or foliage) can be obtained by models of different type, based on the combination of the common measurements of stem diameter at 1.3 m height (D) and tree height (H). The precision of such estimates, however, might be age-dependant (Lehtonen et al. 2004), as the crown architecture changes with age and also due to the competition (Kuuluvainen 1988, Kantola and Makela 2004). Considering that tree growth differs between regions (Wirth et al. 2004, Cienciala et al. 2006, Repola 2009), the existing models might not be applicable in different conditions without a calibration and verification (Albaugh et al. 2009). Thus, models suitable for different regions and stands are necessary to increase the precision of biomass estimation (Cienciala et al. 2006).

In Latvia, *ca* 55% of land area is covered by forests (National Forest Inventory, NFI) and the forest biofuels traditionally has been important source of energy (Dolacis et al. 2005). Although firewood is the most popular fuel for the individual households, during the last decade, the amount of biofuel used for the district heating is rapidly increasing (Broņka and Pelše 2009). According to the data from NFI, Norway spruce is the third most common tree species in Latvia (*ca* 18% of the total forest area). It is economically important species, used for construction, pulp and paper production and energy purposes (Irbe et al. 2012). More than half of all spruce dominated stands in Latvia are planted and, at present, *ca* 25% of all spruce stands have reached the age when thinning should be applied (according to data from NFI). Therefore, from the forest owner perspective, it is important to estimate the biomass available from such stands.

The stem biomass of the common tree species in Latvia may be estimated according to the stem volume tables, which were developed in 1924 and revised in 1960s and 1990s (Sacenieks and Matuzanis 1964, Ozoliņš 1997), and the wood density tables, which were presented by Sacenieks and Matuzanis (1964) and partially revised by Dolacis et al. (2005). However, some data presented in these tables might be outdated, as the alterations in biomass allocation patterns have been observed due to the changes in climate (Hattenschwiler and Korner 1998). Only a few biomass models for some broadleaved species (Miezīte and Dreimanis 2009), and distinct parts of coniferous trees have been recently developed in Latvia (not published). Hence, there is a necessity for a revision and update of the methods used for the estimation of tree biomass. Accordingly, the aim of this study was to develop biomass models that describe the relationships between the aboveground biomass and the dimensions of Norway spruce at the age of 40 years and to compare the precision of the developed models with the models presented by Repola (2009) and estimates from the stem volume tables.

Material and Methods

Study area

The study area was located in the eastern part of Latvia, near Jaunkalsnava (56°42' N, 25°54' E) in the south-western part of Vidzeme upland. The elevation was about 110 metres above the sea level. The relief of the sampling site was flat. According to the data from Latvian Environment, Geology and Meteorology Centre (LEGMC), the mean annual temperature at the study area is *ca* +5 ^{o}C. July is the warmest month (ca 17 ^{o}C) and January is the coldest month (*ca* -6.5 ^{o}C). The mean length of vegetation period (when the mean diurnal temperature is > +5 ^{o}C) at present is *ca* 175 days and it usually extends from late April to October. In general, climatic conditions can be described as moderately continental. The mean annual precipitation is about 700 mm; a half of the annual precipitation falls during the summer months (May – August).

The material was collected in an experimental plantation that consisted of 80 clones of plus-trees of Norway spruce (*Picea abies* (L.) Karst.) selected across the territory of Latvia. Each clone was represented by 60 trees distributed in three replications of 20-tree blocks, planted with the initial spacing of 2 × 2 m. The experiment was started in 1975 with the establishment of mother-plant collection and preparation of grafts. Rooting of the grafts was finalized and trial was planted in 1983 on a drained fertile soil, *Myrtillosa mel.* forest type according to the local classification (Bušs 1979). Systematic thinning (i.e. removing every second tree in a row) was carried out 12 years after the planting. According to the stand inventory, standing volume in 2011 was 246 m^3ha^{-1}.

Sampling

In total, 29 healthy trees were selected for sampling using the stratification approach based on the D distribution of the trial according to the inventory conducted shortly before the sampling. The selected trees were felled; the cutting was done as close to the stem base as possible. Branches were cut from the stems maximally close to the stem surface and collected. It was ensured that all branches broken during the felling were also collected. The fresh weight of the living and dead branches and stem was determined with the precision of 0.01 kg. For each tree, D was measured with a calliper in two directions (with the precision of 0.5 cm) and H (with the precision of 0.01 m) was measured with a measuring tape. From each stem, three stem discs (5 cm in height, from top, middle and bottom parts of the stem), four living branches (subjectively selected mean branch per one quarter of the crown) and four dead branches (subjectively selected mean branches) were collected for the estimation of the wood moisture content (W_0). The samples were transported to the laboratory in closed plastic bags as soon as possible after the collection. In the laboratory, the fresh weight of the samples was determined (with the precision 0.1 g). Then, the samples were dried at 105±2 ^{o}C until the weight was constant and reweighed.

Data analysis

Estimation of models

The correspondence of the measured variables (biomass, D and H) to the normal distribution was tested by the Kolmogorov-Smirnov test (Sokal and Rohlf 1995). For the estimation of the biomass models, the dry weight of each component (stem and branches) and total aboveground part of tree was used as the dependant variable in regression analysis (Sokal and Rohlf 1995). For this reason, moisture content of the sample branches (living and dead) and stem discs for each tree was calculated as (Eqn. 1):

$$W_0 = (m_1 - m)/m_1, \quad (1)$$

where: m_1 is fresh weight of the samples (branches and stem discs), and m is the dry weight of the samples.

For each tree, biomass (dry weight) of living and dead branches and stem was calculated as (Eqn. 2):

$$B = M_1 \times (1 - W_0), \quad (2)$$

where: *M1* is the determined fresh weight, and W_0 is the moisture content of each biomass component.

The dry weight of all branches, stem and whole tree was used for further analysis. Pearson correlation coefficient was used to assess the strength of the relationships between the biomass variables and tree dimensions.

The biomass models for each component and total aboveground biomass were estimated using different model specifications:

linear (Eqn. 3)

$$B=a\times(x)+b, \quad (3)$$

logarithmic (Eqn. 4)

$$B=a\times\ln(x)+b, \quad (4)$$

exponential (Eqn. 5)

$$B=a\times e^{(b\times x)}, \quad (5)$$

power (Eqn. 6)

$$B=a\times x^b, \quad (6)$$

binomial, single independent variable (Eqn. 7)

$$B= a\times x^2+b\times x+c, \quad (7)$$

and linear, two independent variables (Eqn. 8)

$$B=a\times H+b\times D+c, \quad (8)$$

where: *B* is the biomass, *x* is the morphometric variable (*H, D* and several modifications of these variables (H^2, D^2 and D^2H); *a, b* and *c* are the estimates (coefficients) of the fixed variables. The biomass is expressed in kg of dry weight, *H* is used in metres and *D* in centimetres. These model types and predictors were selected as their efficiency for the estimation of the aboveground biomass of conifers has been previously shown by Lehtonen et al. (2004), Mikšys et al. (2007), Pajtik et al. (2008) and Repola (2009). The goodness of fit of the developed models was described by the R^2 and standard error of model residuals. The residuals of the models were tested for normality and heteroscedasticity conducting Shapiro-Wilk and Breusch-Pagan tests, as well as by a graphical inspection.

Validation of the models

The relative errors (deviations) (Eqn. 9) between the estimated and the determined biomass (Rabinovic 2006) were calculated to compare the precision of the developed biomass model, the models presented by Repola (2009) and two previously used stemwood volume tables.

$$\delta = \left|\frac{m_0 - m_1}{m_0}\right| \quad (9)$$

where m_0 is the determined biomass, and m_1 is the estimated biomass.

One of the stemwood volume tables was developed by R. Markus in 1937 and revised by Sacenieks and Matuzanis (1964) and the other table was developed by Ozoliņš (1997). These tables were used for the estimation of stemwood volume. Wood density of freshly cut wood, necessary for the calculation of the fresh weight, was obtained from Dolacis et al. (2005) according to W_0 (*ca* 900 kg m^{-3}). Dry weight of stems was derived from volume tables using the empirical moisture content coefficient for stem (W_0) according to the Eqn. 2. The estimated stem biomass and mean relative errors of the estimates were compared between the calculation techniques using *t*-test for dependant variables (Sokal and Rohlf 1995). The similarity of the patterns of the relative errors of the estimates by the stemwood volume tables and their relationship with the dimensions of trees was assessed by a Pearson correlation analysis. The precision of the models, estimated and presented by Repola (2009), was also described by plotting estimated vs. determined biomass and by a comparison of simulated biomass. Data analysis was conducted with the aid of *R* program v. 3.0.1 (R Core Team 2014).

Results

Measured variables

All variables of the studied trees corresponded to the normal distribution; however, the variation differed amongst them (Table 1). The highest variation (variation coefficient) was observed for the biomass of branches and the lowest for *H*. The variation of the stem and the total aboveground biomass was similar (variation coefficient *ca* 0.30). All of the variables were significantly intercorrelated (Table 2); however, the strength of the correlations differed. Amongst the biomass variables, the highest correlation was observed between the stem and the total aboveground biomass ($r = 0.962$), suggesting nearly the same variation. The correlation between the tree dimensions (*D* and *H*) was intermediate ($r = 0.682$), suggesting different sources of the variation and that the use of both dimensions might provide a better explanation of biomass components. The weakest correla-

Table 1. Statistics (range and mean value, coefficient of variation and relative standard error) of the tree characteristics – biomass of branches, stem and aboveground part, proportion of stem biomass, tree height (H) and stem diameter at 1.3 m height (D) of the sampled Norway spruce

	Stem biomass (kg)	Branch biomass (kg)	Above-ground biomass (kg)	Proportion of stem biomass	D, cm	H, m
Min	36.29	8.70	44.98	0.63	11.79	14.20
Max	124.34	74.54	197.52	0.85	24.35	18.70
Mean	85.58	25.40	110.94	0.78	18.36	16.42
Variation coefficient	0.31	0.50	0.32	0.07	0.17	0.08
Relative standard error	0.06	0.09	0.06	0.01	0.03	0.02

Table 2. Pearson correlation coefficients (r, upper diagonal part of the table) and their significance level (p-values, lowed diagonal part of the table) between tree characteristics: biomass of branches, stem and aboveground parts, stem diameter at 1.3 m height and tree height (H) for 40-year Norway spruce

	Stem biomass	Branch biomass	Aboveground biomass	D	H
Stem biomass	*****	0.64	0.96	0.91	0.82
Branch biomass	<0.01	*****	0.83	0.72	0.39
Aboveground biomass	<0.01	<0.01	*****	0.93	0.74
D	<0.01	<0.01	<0.01	*****	0.68
H	<0.01	0.03	<0.01	<0.01	*****

tion was observed between the branch biomass and *H*, suggesting influence of variables other than dimensions of tree.

Developed models

The explanatory power of the developed models differed notably according to the model type, biomass component (response variable) and the independent variables used, as shown by the range of R^2 and the standard errors of the residuals (Table 3). In general, models developed for the stem and the total aboveground biomass showed better fit to the estimated data, irrespectively of the independent variables, compared to the models of branch biomass, which were less precise (mean R^2 coefficients of all tested models were 0.77 and 0.73 against 0.41, respectively). The stem and the total aboveground biomass was estimated most precisely by the models based on both tree dimensions (*D* and *H*), while the branch biomass showed the strongest dependence on *D* alone (Table 3). The types of the models showing the highest R^2 values differed between the components of biomass; still, the power models showed the best fit in cases of the branch and the total aboveground biomass.

The linear model, based on *D* and *H* as two independent variables, provided the best estimates of the stem biomass as shown by the highest R^2 ($R^2 > 0.900$) and the lowest residual standard error (Table 3, 4). The mean relative error of these estimates from the determined biomass was *ca* 8.1%. The D^2H as an independent variable was the best predictor for the total aboveground biomass ($R^2 > 0.900$) (Table 4) and the mean relative error of the estimates was *ca* 8.6%. The estimated values of the stem and the total aboveground biomass were proportional to the determined values and the residuals were homoscedastic (Figure 1). The highest R^2 value of the best developed model for the branch biomass ($R^2 = 0.639$) was notably lower compared to the stem biomass model (Table 4) as also suggested by the lower correlation with tree variables (Table 2). Such imprecisions were also reflected in a higher relative error of the estimate *ca* 20.2%. The comparison of the estimated and the determined values of the branch biomass showed that the residuals of the model appeared more heteroscedastic (Figure 1), suggesting increasing biasness of the estimates particularly for the larger trees, for which the branch biomass was underestimated. Still, all of the parameters of the fixed variables of the best models (Table 4) were significant and *p*-values did not exceed 0.03, and, in most cases, they were < 0.01. All model parameters, except the constant in the linear model, were positive, suggesting positive relationships between the tree dimensions and the biomass components.

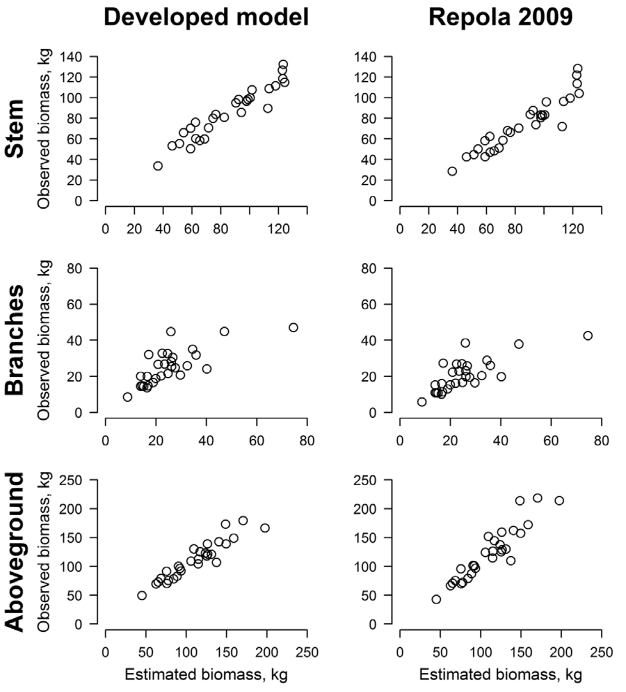

Figure 1. The relationships between the biomass estimates made by the developed models and models presented by Repola (2009) and the determined biomass for the components of the aboveground parts of 40 years old Norway spruce

Comparison of biomass estimates

The mean values of the biomass estimated by the developed models significantly (*p*-value < 0.01) differed from the estimates made by the models presented by Repola (2009), which significantly (*p*-value < 0.01) differed from the determined biomass. The Repola (2009) models underestimated the biomass of stem and branches, but overestimated the total aboveground biomass, particularly for trees with higher dimensions (Figure 2). Hence, the estimates by Repola (2009) model had higher relative errors – 14, 26 and 13% for stem, branch and total aboveground biomass, respectively. The residuals of the Repola (2009) model were more heteroscedastic (Figure 1) compared to the developed models, suggesting stronger biasness of the estimates for trees with larger dimensions. Mainly, for both the developed and the Repola (2009) models, *D* and *H* had a positive effect on the biomass (Figure 2); nevertheless, the estimates of branch biomass by the Repola (2009) model showed negative relationships (slightly decreasing slope) with H.

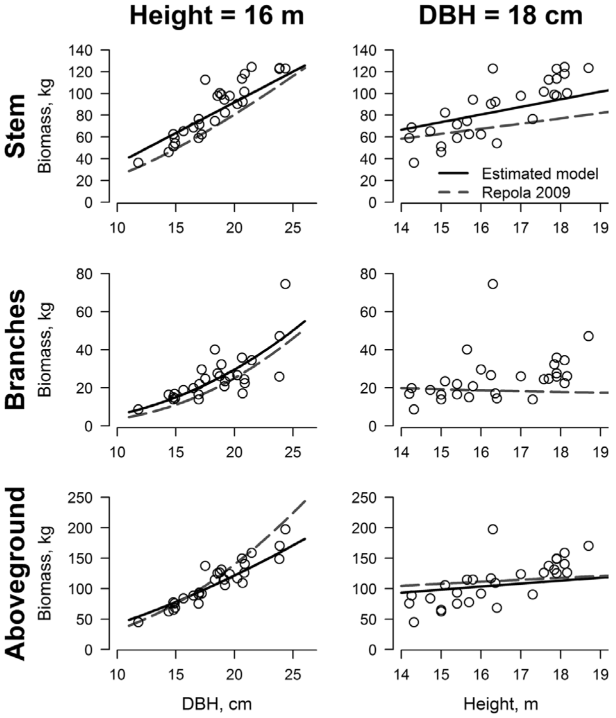

Figure 2. Simulated biomass of the compartments of the aboveground biomass of 40-years old Norway spruce using the developed and Repola (2009) models. Simulations were made within the range of the observed values with one of the variables as constant (~ mean of the observed values). Circles show the estimated values

The precision of the developed models appeared to be slightly higher compared to the previously used wood volume tables as the mean relative errors from the determined stem biomass were 8.1 and 10.5%, respectively. Still, the stem biomass estimates of the developed models and the volume tables, as well as their relative errors were similar (p-values of differences > 0.05). The range of the relative errors was similar for all three estimates; however, use of volume tables developed by Sacenieks and Matuzanis (1964) resulted in higher number of biased values (Figure 3). The relative errors of the developed models and volume tables showed significant correlation ($|r|$ ~0.60) suggesting similar patterns of biasness (Table 5). The relative errors were more similar for both of the tested volume tables as shown by higher correlation ($r = 0.95$) (Table 5). The relative errors of biomass estimates made by wood volume tables of Ozoliņš (1997) significantly correlated with D suggesting heteroscedasticity and systematic bias of the estimates. Additionally, wood volume tables underestimate stem biomass (stem volume) of trees of the larger dimensions and overestimate volume of the smallest trees.

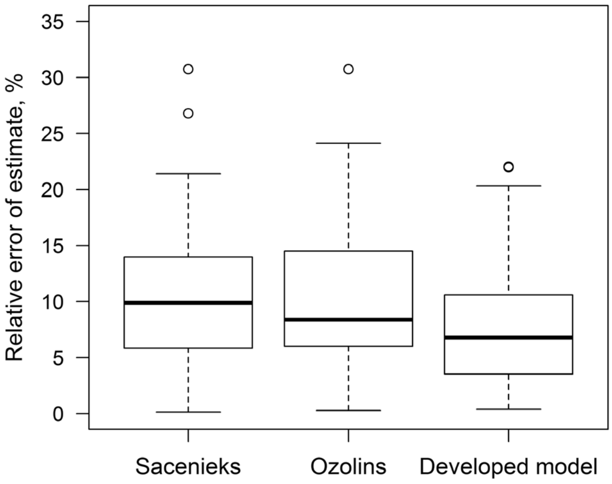

Figure 3. Mean relative errors of the stem biomass estimated by the developed model and by volume tables presented by Sacenieks and Matuzanis (1964) (Sacenieks) and Ozoliņš (1997) (Ozolins)

Discussion

Commercial thinning of spruce stands in Eastern Europe is normally started, when the stand has reached age of 30-40 years (Zālītis 2006) and a certain amount of the removed biomass can be utilized for energy (Zālītis 2006, Broņka and Pelše 2009). Our results suggest that the amounts of the biomass removed during such thinning may be estimated quite accurately by the developed models based on the dimensions (Table 3). Still, not all of the tested models were equally accurate for the different components of the total aboveground biomass of Norway spruce. The errors of the model estimated for branch biomass, which are most likely used as fuel (Lazdāns et al. 2009), was higher than for the stem biomass (Tables 3, 4) suggesting that D and H alone might not be completely sufficient predictors due to the competition within the stand that affects the shape of crowns (Kuuluvainen 1988, Kantola and Makela 2004). This is also suggested by the stronger effect of single D, which is related with social status of tree (Hamilton 1986) than combination of D and H on branch biomass (Table 3). Nevertheless, the model parameters of the branch biomass component were significant, thus the estimates of the branch biomass made by the developed model (Table 4) were significant. The biomass of the stem, which formed the largest part of the aboveground biomass (Table 1), was best predicted by the combination of D and H (Table 4) as previously shown by Mikšys et al. (2007), Pajtik et al. (2008) and Repola (2009). This suggests that the tree dimensions, when used together, are good predictors ($R^2 > 0.900$) of stem and the total aboveground biomass of tree, despite significant correlation between D and H (Table 2) and lower accuracy of the model developed for branch biomass estimates (Table 4). Good fit of the developed models to stem and total aboveground biomass data can be explained by the stronger regulations of the stem size as the variation in stem taper for trees grown in similar conditions is usually low (Bruchert et al. 2000). The similarity of the predictors for the stem and the total aboveground biomass, however, might be explained by the high correlation observed between them ($r = 0.962$, Table 2). Nevertheless, different types of models that showed the best fit to the stem and the total aboveground biomass (Table 4), suggested that there are slight differences in the effect of each tree dimension on biomass (Mikšys et al. 2007). Linear type and similar coefficients (considering their standard errors) of the model showing best fit to stem biomass (Table 4, Figure 2) suggested that both tree dimensions (D and H) had a comparable effect on the stem biomass. However, the effect of D on the aboveground biomass was stronger compared to H, as suggested by a better fit of the models based on D to the determined weight, when the tree dimensions were tested individually (Table 3, Figure 2).

The biomass estimates made by the models presented by Repola (2009) appeared less precise compared to the developed models, irrespectively of the biomass component (Figures 1, 2) contradicting the direct application of non-verified models. Such biasness can be explained by the geographic specifics in resource allocation in trees (Hattenschwiler and Korner 1998, Albaugh et al. 2009). The models presented by Repola (2009) were developed for boreal conditions, where the tree properties such as the stem temper and wood density may differ (Newnham 1992, Bruchert 2000 et al.).

The stem biomass estimated by the developed model and the volume tables did not differ significantly (p-value > 0.05). However, the developed models provided slightly higher accuracy (slightly lower relative errors) of the aboveground biomass compared to the stemwood volume tables (Figure 3), which were developed for unimproved material and/or wider geographic range (Sacenieks and Matuzanis 1964, Ozoliņš 1997). Still, the errors of these biomass estimates did not differ significantly ($0.05 < p$-value < 0.10), suggesting similar biasness of both estimates. Nonetheless, the relative errors of volume tables correlated significantly with D, suggesting systematic bias in these estimates. Apparently, the variability of D has not been considered in volume tables completely, hence, the volume tables for the estimation of the stem biomass of Norway spruce should be used sparingly. Thus, precise models suitable for a wider application, which account for the differences amongst stands, are necessary to increase the precision of biomass estimates (Classon et al. 2001, Lambert et al. 2005, Pajtik et al. 2008, Repola 2009). Even though, the developed models at present appear the most precise method for the estimation of the aboveground biomass and its components of Norway spruce in the eastern part of Latvia despite the limitations for wider application of these models.

Conclusions

The aboveground biomass of 40-years old spruce in the eastern part of Latvia can be estimated by the linear and power models. The biomass of stem and the total aboveground parts of spruce was best estimated by a linear combination of D and H and D^2H, respectively. The estimates of branch biomass were based on D, but appeared less precise, likely due to the differences in crown shape. The developed models showed notably higher precision than Repola (2009) models for all components of biomass, but only slightly higher precision compared to the previously used stemwood volume tables, which, however, partially underestimated the effect of D.

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