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Aboveground dendromass allometry of hybrid black poplars for energy crops

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Abstract. Cultivation of energy crops is concerned with estimation of the total lignified biomass (dendromass) production, which is based on the plantation density and individual plant dendromass. The main objective of this study was to investigate the allometry of aboveground leafless biomass of juvenile black poplar hybrids (*Populus deltoides* x *P. nigra*), traditionally used for timber and cellulose production, and to derive generic allometric models for dendromass prediction, relevant to energy crop cultivation in Bulgaria. The study material comprised a variety of growth sites, tree ages and clones, specific to poplar plantings in Bulgaria. We used three principal quantitative predictors: diameter at breast height, total tree height and mean stand (stock) height. The models were not differentiated by clone, because the black poplar hybrids tested were not equally represented in the data, and the inclusion of tree age as a predictor variable seemed unreliable, because of the significant, up to 3 years, variation, which was possible within the narrow age range investigated. We defined the mean stand (stock) height as a composite quantitative variable, which reflected the interaction between the time since planting (age), site quality and the intrinsic growth potential. Stepwise and backward multiple regression analyses were applied to these quantitative variables and their products and sets of adequacy and goodness-of-fit criteria were used to derive individual biomass models for stem and branches. Then we developed compatible additive systems of models for stem, branch and total lignified biomass in log-transformed form. Finally, the prediction data were back-transformed, applying correction for bias, and were cross-validated. Three systems of generic equations were derived to enable flexible model implementation. Equation system M1 proposes a stem biomass model based on tree and stand heights and stem diameter, and a model for branches including mean stand height and breast height diameter; this model displayed the best goodness-of-fit characteristics. Model system M2 uses only the tree height and diameter and therefore is most relevant to dendromass determination in single trees or harvested saplings, while model M3 allows fast and sufficiently accurate biomass estimation of standing

poplar stock, because it employs the average stand height and the individual tree diameters. All models are applicable to predict lignified aboveground biomass of juvenile *Populus deltoides* x *P. nigra* trees of diameter up to 21 cm and total height up to 16 m.
Keywords aboveground dendromass, black poplar hybrids, allometric relationships, lignocellulosic crops, short-rotation plantations

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Introduction

Ongoing climate change and the much-discussed depletion of fossil fuel resources have increased the focus on renewable energy during recent decades. The forests and sustainable forest management provide renewable raw material and energy supply, and wood has been recognized as one of the main biomass reservoirs. Two principal sources of dendromass have been identified: the remains from timber harvesting and the wood-processing industry, and short-rotation crops from fast-growing tree species; the latter is given higher priority in Europe (Ericsson et al. 2006).

Cultivation of short-rotation crops usually involves estimation of the total lignified biomass production, which is based on plantation density and individual plant dendromass. Volume, assortment, growth and yield tables have been developed for proper timber appraisal and management of black poplar hybrids in Bulgaria (Krastanov et al. 2004a, b), but the allometric patterns of the lignified biomass at early stages of growth and in relation to energy crop cultivation have not yet been investigated. Most studies on energy crops use the general allometric equation (Huxley 1972), by relating the dry biomass weight to a power function of tree diameter at a certain height above ground to evaluate the individual plant mass (Walle et al. 2007, Paris et al. 2011, Verlinden et al. 2015). The resulting estimates are reliable since the power-law relationships are characterized by scale invariance (self-similarity) and universality (Marquet et al. 2005). However, the derived allometries are species/genotype-, site- and age-specific and expansion of the predictions of such peculiar, local-type models to larger scales would lead to biased predictions due to the likely dependence of the relationships on the growth conditions and stand characteristics.

Some of the hybrid black poplar clones (*Populus deltoides* x *P. nigra*) are described as having thin branches (‘I 45 51’,’Agathe’, ‘Luisa Avanzo’), while thick branches are characteristic of other clones (e.g. ‘I 214’) (Tsanov & Mikov 1997). A study by Sixto et al. (2014) showed that clone ‘I 214’ and particularly ‘MC’ are characterized by relatively low branchiness. These observations suggest that the biomass allometry of hybrid black poplars might be clone-specific. Previous research on other species has shown that biomass allocation may depend also on site factors and stage of stand development (Porté et al. 2002, Arrevalo et al. 2007, Paul et al. 2013a,b). Twelve types of sites afforested with poplars have been distinguished in Bulgaria (Marinov et al. 1982). These are grouped into three categories according to their geographical location (along the bank of Danube, along the banks of the interior rivers and in wet valleys), and the principal criterion for their classification is the availability of underground water. Consideration of stand age, as suggested by e.g. Porté et al. (2002) and Bond-Lamberty et al. (2002), along with clone and site, as other possible covariates in the biomass models would yield a huge number of clone x site x age combinations, and development of a local model for each particular combination would be unjustified and unreasonable. Studies by Paul et al. (2013a,b) also suggest that each such combination must include at least 6-7 measurements for consideration in the analyses (e.g. ANCOVA), which would greatly increase the time and effort required for data collection.

Alternatively, generalized deterministic and mixed-effects model forms have been considered as different ways of localizing allometric models to specific stands (Stankova & Dieguéz-Aranda 2013). While purely deterministic model specifies the biomass allometry by inclusion of stand-level predictor variables (e.g. Bond-Lamberty et al. 2002; Shaiek et al. 2011), the mixed-effects model characterizes the variability between different locations through the random components of the model parameters; the latter cannot be applied appropriately without a supplementary sample of observations or stand-level data to calibrate the random components (Stankova & Dieguéz-Aranda 2013). The main objective of this study was to investigate the allometry of aboveground leafless biomass of juvenile black poplar hybrids (*Populus deltoides* x *P. nigra*), traditionally used for timber and cellulose production, and to derive biologically and statistically sound generalized (generic) models for dendromass prediction, relevant to cultivation of energy crops in Bulgaria.

Materials and methods

Data collection

Data and sample collection took place in 2 to 6-year-old 1) industrial and 2) experimental poplar plantations and in 3) an experimental nursery plantation of one-year-old saplings (Table 1). The first data source consisted of the fifteen permanent sample plots in hybrid black poplar (*Populus deltoides* x *P. nigra*) plantations destined for timber production, which were used to parameterize biometric models for the total aboveground biomass and is described in detail in Stankova et al. (2015). The second data source was presented by 250 m^2 experimental plot of clone 'I 214' (Table 1) established on cultivated, carbonate-rich Haplic Kastanozem in the proximity of a cement plant near a tributary of the river Iskar in north-western Bulgaria, where dendromass of respectively 5 and 3 trees was sampled at ages 2 (March 2012) and 4 (November 2013) years (Table 1). The third sampling source was an experimental plantation growing on 4284 m^2 of nursery land near Danube and consisting of four poplar clones planted at three initial densities (Table 1). The trial plantation was established on Haplic Kastanozem in March 2014, in a randomized complete block design with four replications. Each plot (clone´density combination) was arranged in double-row plantation design with alternating inter-row distances of 0.5 and 1.8 m. The intervals between the plants within the rows were 0.5, 0.75 and 1m, yielding overall planting densities of 17390, 11595 and 8700 stems per hectare, respectively. Twenty-six plants per clone (3 to 6 trees per clone x density x replication combination from two of the blocks) were sampled from 100% rooted 3 m-long strips of the rows in November 2014 (Table 1). Dendromass data of trees that had both stem and branches (44 saplings) were used in the data analysis to avoid possible experimental error due to subjective factors. For all data subsets, mean stand/stock height was

Table 1 Description of the experimental data used to derive the aboveground dendromass models

Lot	Clone	Planting scheme (m x m)	Plant age (years)	Sampled trees	*dbh* (cm)[a]	*h* (m)[a]	*H* (m)[a]	w_s (kg)[a]	w_b (kg)[a]	w_t (kg)[a]
P1	Agathe	6x5	2	2	3.5 (3.0-4.1)	4.0 (3.8-4.1)	4	1.058 (0.723-1.392)	0.186 (0.142-0.231)	1.244 (0.866-1.623)
P2	I 45 51	5x5	5	3	9.2 (6.5-10.9)	6.6 (4.2-8.2)	7	8.109 (3.038-11.070)	3.849 (1.342-6.168)	4.380 (11.952-17.238)
P3	I 214	6x5	5	4	12.9 (10.7-14.3)	10.0 (9.0-11.1)	11	17.588 (12.805-24.680)	2.814 (1.945-4.458)	20.403 (14.896-29.139)
P4	I 214	6x5	6	6	17.3 (13.6-21.2)	12.2 (10.8-13.8)	14	39.607 (23.466-69.885)	17.060 (4.059-31.111)	56.667 (27.524-100.996)
P5	I 214	6x5	2	2	3.2 (2.8-3.6)	3.0 (3.0-3.1)	3	0.544 (0.479-0.609)	0.284 (0.199-0.369)	0.828 (0.678-0.979)
P6	I 214	6x3	6	4	17.9 (15.3-21.0)	14.3 (13.5-15.1)	16	48.514 (36.492-66.287)	23.473 (11.863-35.006)	71.987 (48.356-94.956)
P7	I 45 51	5x5	5	3	17.1 (15.0-19.3)	14.3 (13.8-14.7)	14	47.604 (38.432-61.801)	10.386 (6.122-13.822)	57.990 (44.554-75.622)
P8	I 214	5x5	5	3	11.8 (9.7-14.2)	11.0 (10.2-11.4)	11	22.319 (13.176-30.791)	6.075 (3.375-9.717)	28.394 (16.551-40.508)
P9	I 45 51	5x5	3	3	2.7 (2.2-3.1)	4.2 (3.8-4.5)	4	0.582 (0.369-0.768)	0.027 (0.014-0.037)	0.608 (0.382-0.805)
P10	NNDV	5x5	2	3	3.4 (2.9-3.6)	4.8 (4.4-5.0)	5	0.973 (0.682-1.171)	0.116 (0.074-0.142)	1.089 (0.756-1.312)
P11	MC	5x5	3	5	6.6 (2.9-9.7)	7.3 (4.3-9.2)	9	6.502 (0.725-12.461)	0.724 (0.078-1.216)	7.226 (0.803-13.677)
P12	Agathe	5x5	4	3	14.2 (12.8-15.5)	12.2 (11.7-12.6)	13	30.652 (27.243-36.125)	8.405 (8.100-8.822)	39.058 (35.538-44.225)
P13	I 214	5x5	2	3	2.6 (2.3-3.0)	4.3 (3.7-4.7)	4	0.667 (0.412-0.913)	0.033 (0.029-0.039)	0.700 (0.440-0.952)
P14	I 214	5x5	6	3	8.9 (6.0-10.7)	8.3 (6.3-9.9)	10	10.080 (3.078-13.611)	3.542 (1.136-4.960)	13.622 (4.214-18.511)
P15	I 214	5x5	4	3	4.2 (3.6-5.0)	5.6 (5.1-6.1)	6	1.746 (1.132-2.412)	0.257 (0.211-0.325)	2.003 (1.343-2.737)
EP1-1	I 214	2x1	2	5	2.4 (1.9-2.9)	3.4 (2.9-3.8)	4	0.405 (0.281-0.539)	0.144 (0.065-0.209)	0.548 (0.346-0.742)
EP1-2	I 214	2x1	4	3	4.8 (1.4-8.1)	5.9 (4.5-7.3)	5.3 (5-6)	2.135 (0.793-6.123)	1.038 (0.275-2.144)	4.172 (1.068-8.267)
NS1	I 214	1.15x0.5, 1.15x0.75, 1.15x1	1	26	1.1 (0.7-1.4)	2.2 (1.4-2.7)	2	0.124 (0.046-0.204)	0.004 (0.002-0.007)	0.130 (0.074-0.167)
NS2	Luiza Avanzo	1.15x0.5, 1.15x0.75, 1.15x1	1	26	1.2 (0.6-1.7)	2.4 (1.7-3.1)	2.2 (2-3)	0.132 (0.047-0.227)	0.015 (0.002-0.032)	0.172 (0.092-0.250)
NS3	MC	1.15ξ0.5, 1.15ξ0.75, 1.15ξ1	1	26	1.2 (0.8-1.7)	2.2 (1.3-2.8)	2	0.132 (0.026-0.221)	0.032	0.231
NS4	I 37 61	1.15x0.5, 1.15x0.75, 1.15x1	1	26	1.4 (0.7-2.0)	2.4 (1.4-3.1)	2	0.170 (0.039-0.336)	0.019 (0.004-0.055)	0.208 (0.076-0.373)

Note. Abbreviations: P – sample from industrial plantation, EP – sample from experimental plantation, NS – sample from experimental nursery stock; *dbh* – breast height diameter of the tree (cm), *h* – total tree height (m); *H* - average height of the stand/stock to the nearest meter (m); *ws* – dry biomass of stem (kg); *wb* – dry biomass of branches (kg); *wt* – total aboveground dry dendromass of the tree (kg); *a* - average variable values with minimum and maximum values shown in brackets.

determined from the plot data as a weighted average according to the tree basal areas (Lorey's formula).

Each sample tree was cut to the ground at 5 cm maximum stump height, and stem length and breast-height tree diameter were measured to the nearest 1.0 cm and 0.1 cm, respectively.

The stem and the branches of each tree were separated and weighted *in situ*, to the nearest 0.005 kg. Five stem and 3 branch samples from each plantation-grown tree, and 1 stem and 1 branch samples per clone x density x replication combination of the experimental nursery stock were assembled and their fresh weight was measured in the field. The samples were oven-dried at 105 °C to constant weight and measured to the nearest 0.001 kg. Proportion of dry mass relative to the fresh sample weight was averaged from the samples of each fraction within the tree and was used to estimate the total amount of dry mass of the respective tree compartment.

Modelling rationale

Energy crops have been defined as short-rotation, high-density systems of selected genotypes grown under specific cultural regimes (Ceulemans & Deraedt 1999). Ceulemans & Deraedt (1999) reported that optimum rotation time and plantation density for poplar energy plantations are generally 4 years and 2500 to 10 000 plants per hectare, respectively. Consequently, the poplar crops cultivated for timber and cellulose production (the first data source) do not provide the most representative data for our study. Branches are usually removed from saplings in nursery stocks during the first year to encourage stem growth. For this reason, we only used one-year-old ramets from an experimental nursery plantation, designed to investigate poplar clones and stocking rates relevant to short-rotation cropping. Sampling of older plants, 2 to 6 years of age, was possible mainly from industrial plantations at planting density as low as 330-550 stems per hectare (Table 1). This influenced our sampling data in two ways. First, the range of tree sizes explored was greatly extended due to the large, practically unrestricted by competition, growth space. This specificity of the data set was addressed by applying rigorous tests on the data-model agreement, such as tests for outliers, influential and leverage points (Table 2), which detect whether certain observations exert undue "influence" on the coefficients of one model compared to another (Sileshi 2014). The second peculiarity of the plantation data was that the saplings used for afforestation were exposed to the already-mentioned pruning during the first year of growth in the nursery. Although pruning is a management activity aimed at growing high quality timber, it can be expected to change the ratio between the aboveground woody compartments, increasing the proportion of the stem at the cost of the branches. However, removal of branches would inevitably be balanced by development of new twigs due to the release of additional nutrients and to the need to recover the reduced photosynthetic area. We assumed that the equilibrium between the tree dimensions (e.g. height and diameter) and the biomass of the tree fractions will be restored within a short time, e.g. during the first vegetation period after the plantation establishment, and the noted data deficiency will be offset. Our assumption is in agreement with the concept of a dynamic model of plant growth (GreenPlant) by Mathieu et al. (2009) where the plant is considered as a collection of interacting 'sinks' that compete for the allocation of photosynthates coming from 'sources'. Based on the model, the authors derived the inference that in the early stages of plant growth, the ratio of biomass to demand increases and induces a fast increase in the growth unit size, which then stabilizes and oscillates due to the appearance of branches (Mathieu et al. 2009). In concordance with our assumption, Desrochers et al. (2015) found that hybrid poplar trees pruned to 2/3 crown length produced nearly twice as many epicormic branches with over twice the biomass of 1/3 pruned trees within 2 vegetation periods, which was interpreted as a means for trees to restore the balance between leaf area and non-photosynthetic organs. However, the specificities of our data deduce the tentative nature of the derived dendromass models and for this reason they must be viewed as preliminary. They can be applied for estimation of aboveground lignified biomass from black poplar energy crops until more appropriate data are collected and the estimation procedure is repeated to develop new generic allometric models.

We applied analytical data screening and biological rationale to combine the factors influencing the studied biometric relationships into a smaller number of predictor variables. The number of the trees, which we sampled from each clone was proportional to its availability in the poplar plantings. Therefore, the black poplar hybrids investigated here were not equally presented in our data set and considering also the limited amount of data, which we utilized (102 trees), we did not differentiate our models according to clone. Our decision is supported by the conclusion of Al Afas et al. (2008), who studied 17 poplar clones belonging to six parentages and found that one equation could be used to estimate aboveground biomass production of all clones. Our choice to disregard the clone as a categorical predictor variable was substantiated also by the statement by Sileshi (2014) that a sample size of around 50 is required to estimate parameters accurately with Ordinary Least-Squares, if only breast-height tree diameter is used as a predictor, but with multiple predictors the sample size must be doubled or tripled depending on the number of parameters to be estimated.

Replanting is usually carried out during the first three years after establishment of industrial plantations, to replace dead plants. The trees in the plantation may therefore differ in age by as much as 3 years, which is a significant variation considering the narrow age range investigated; therefore the inclusion of tree age as a predictor variable seemed unreliable. Data collection took place on a variety of growth sites and soil types along the banks of rivers Danube (northern Bulgaria), Maritsa and its tributaries (south-eastern Bulgaria), and on agricultural land near a tributary of the river Iskar in north-western Bulgaria. The average height of a stand or stock is a very good indicator of site quality and can also be used instead of age as an indicator of growth stage (Stankova & Shibuya 2003). Unlike age, larger mean height will reflect not only the time since plantation establishment, but also better site quality and management on the one hand and stronger growth potential due to genetic factors (intrinsic growth rate, resistance and tolerance to adverse conditions) on the other. Consequently, it can be viewed as a composite quantitative variable, a product of the interaction between time since establishment and the growth conditions (abiotic and biotic). Li & Zhao (2013) stated that at large scales, such as the national level, height varies widely for a given diameter and that differences in tree height at the same breast height diameter also suggest differences in site quality. Taeroe et al. (2015), who investigated biomass allometry of a hybrid poplar clone *Populus trichocarpa* x *Populus maximowiczii* (OP42) across southern Scandinavia using mixed-effects models to account for the variation due to site, found that model with only diameter at breast height (*dbh*) as predictor variable differed significantly among sites, but the inclusion of height as a predictor removed the site effect. We therefore considered total tree height (h) and mean stand/stock height H (m) as appropriate to localize the diameter-based allometric models to specific poplar stands/stocks and we finally used three principal quantitative independent variables: diameter at breast height, total tree height and mean stand (stock) height.

Model development

We examined the three selected quantitative variables and their products [ln(*dbh*), ln(*h*), ln(*H*), *dbh*, *h*, *H*, ln(*h* x dbh^2), (ln(*dbh*))^2, ln(dbh^2), dbh/h^2, *H* x *dbh*, *H* x *h*, *h* x dbh^2, dbh^2, ln(dbh/h^2), 1/*dbh*, 1/*h*, ln(*H* x dbh^2), dbh/H^2, *H* x dbh^2, ln(dbh/H^2), 1/*H*) as predictors of the log-transformed aboveground dry mass of the lignified tree compartments (stem and branches) by stepwise and backward multiple linear regression analyses (Clutter et al. 1983). Collinearity of the models, which were derived (parameter estimates significantly different from zero at $P < 0.05$), was assessed and controlled by estimating the condition number (Canga et al. 2013, Menéndez-Miguélez et al. 2013). When a value above 30 was obtained, and considering the correlation matrix of the predictor variables, reduced-form model combinations were tested and proposed instead. Models with the selected predictor variables were then formulated and fitted by Ordinary Least-Squares Method (OLS). The model adequacy was assessed according to the requirement for biologically-logical model behaviour, by the adjusted coefficient of determination (Radj.), the root mean squared error (RMSE) and Akaike information criterion (AIC) and by a set of other nine model selection criteria (Stankova et al. 2015), derived from Gadow & Hui (1999), Paressol (1999), Picard et al. (2012) and Sileshi (2014), and shown in Tables 2 and 3.

Next, the best models for each tree compartment were combined in a system of equations that were fitted simultaneously by applying Seemingly Unrelated Regression (SUR) to consider the cross-equation correlations (Parresol 1999, Burkhart & Tomé 2012) and taking into account the system additivity, which required that the estimate of the total lignified aboveground biomass equals the sum of the estimates of the individual compartments.

Log-linear regressions were preferred for fitting the final regression equations, as suggested by Xiao et al. (2011) and Sileshi (2014), due to the multiplicative, heteroscedastic, lognormal error distribution. To convert the predicted values to arithmetic, untransformed units, additional correction for bias was required (Parresol 1999) and the ratio correction (Clifford et al. 2013) was applied. Correction for bias was performed for each of the tree compartments separately, followed by their summation to obtain unbiased estimate of the total lignified biomass. The corrections of the back-transformed data were followed by tests for mean errors equalling zero and two additional goodness-of-fit tests (Table 4): Mean absolute relative error (MARE%), which shows the magnitude of the average absolute deviation relative to the value of the modelled variable and Model efficiency (ME), which is a relative measure of model performance analogous to the coefficient of determination, but of ideal value equal to zero (Gadow & Hui 1999).

Cross validation is an important procedure in the development of predictive models and in this study, it was specifically adapted by considering that the total data set was limited to 102 observations. When the data do not have sufficient observations to create sizable parametrization and validation data sets that represent the population well, the K-fold cross validation is an attractive alternative with 5-fold or 10-fold cross validation providing a good balance between bias and variance (Sileshi 2014). We performed 1000 runs, in each of which 20% of the observations were randomly selected for validation, while the remaining 80% were used to fit the models (i.e. 1000 runs of 5-fold cross-validation). Mean error and error variance were assessed for both the prediction and the validation data sets at the end of each run. The final mean error and error variance values that were compared were estimated as the average values over the thousand simulations.

Table 2 Model systems for the aboveground dendromass compartments of hybrid black poplars – goodness-of-fit tests

	Model	RMSE	Mean error [a]	R_{adj}	AIC	Anderson-Darling test statistic [b]	Breusch-Pagan test statistic [b]	Model bias (*F*-test) [c]	Condition Number [d]	Outliers (%) [e]	Leverage points (%) [e]	Influential points (%) [e]
M1	$\ln w_s = b_0 + b_1 \ln(h) + b_2 dbh/h^2 + b_3 H \ln(dbh)$	0.151	0.007	0.995	-384.0	0.559	0.128	0.113	28.729	2.94	0.98	1.96
	$\ln w_b = a_0 + a_1 \ln(dbh) + \ln(H)$	0.707	-0.011	0.938	-69.7	0.373	6.080	1.113		4.90	2.94	5.88
	$\ln w_t = \ln(\exp(a_0) H dbh^{a_1} + \exp(b_0) h^{b_1} \exp(b_2 dbh / h^2) dbh^{b_3 H})$	0.179	-0.008	0.994	-347.9	0.703	0.560	0.446		2.94	1.96	1.96
M2	$\ln w_s = b_0 + b_1 (\ln(dbh))^2 + b_2/h$	0.166	0.008	0.994	-364.7	0.301	0.159	0.114	12.084	3.92	0	0
	$\ln w_b = a_0 + a_1 \ln(dbh) + \ln(h)$	0.732	0.044	0.933	-62.6	0.466	5.974	0.831		4.90	0.98	5.88
	$\ln w_t = \ln(\exp(a_0) h dbh^{a_1} + \exp(b_0) dbh^{b_1 \ln(dbh)} \exp(b_2 / h))$	0.193	-0.003	0.993	-333.2	0.466	1.329	0.211		5.88	0.98	0.98
M3	$\ln w_s = b_0 + b_1 (\ln(dbh))^2 + b_2 \ln(H)$	0.339	-0.015	0.976	-218.91	0.329	5.454	0.233	13.933	3.92	0	0
	$\ln w_b = a_0 + 2\ln(dbh) + \ln(H)$	0.700	0.052	0.939	-72.15	0.483	5.536	0.328		4.90	0	1.96
	$\ln w_t = \ln(\exp(a_0) H dbh^2 + \exp(b_0) dbh^{b_1 \ln(dbh)} H^{b_2})$	0.324	-0.020	0.980	-228.10	0.182	5.932	0.379		5.88	2.94	1.96

Note. [a] Mean errors are not significantly different from zero in all cases; [b] Null hypotheses for normality (Anderson- Darling test) and homoscedasticity (Breusch –Pagan test) of errors are accepted in all cases, as P>0.05. [c] Null hypothesis for slope equal to 1 and zero intercept of the linear regression relating observed and predicted values is accepted in all cases, as P>0.05; [d] Defined as a criterion for collinearity and must obtain values below 30; [e] Outliers in the response variable are assessed by the percentage of Studentised residuals within [-2; 2]. Leverage points are outliers with respect to the predictors and are compared to a reference value estimated as: 2(k+1)/n, where k is the number of predictors and n is the sample size. The influential points (Cook's D) are predictor combinations with unusually large weights in determining regression coefficients and are compared to a reference value estimated as: 4/n, n - sample size. The percentage of the influential observations, exceeding the reference values, must obtain value below 10%.

Abreviations: *dbh* - breast height diameter of the tree (cm), *h* - total tree height (m); *H* - average height of the stand/stock to the nearest meter (m); w_s - dry biomass of stem (kg); w_b - dry biomass of branches (kg); w_t - total woody biomass: stem+branches (kg); RMSE - root mean squared error (kg); R_{adj} - adjusted coefficient of determination; AIC - Akaike Information Criterion

Results

Three models were derived for dry stem biomass of hybrid black poplars as an outcome of the multiple linear regression analyses, but we could not derive an adequate model for the dry biomass of branches by means of stepwise and backward multiple regressions, and we therefore tested the five principal model formulations recommended by Clutter et al. (1983) and Burkhart & Tomé (2012) for modelling tree volume and biomass: combined variable, constant form factor, logarithmic, generalised logarithmic and Honer transformed variable models. Combinations of the selected stem and branch models were then formulated and examined to derive systems of equations for predicting the lignified aboveground biomass of hybrid black poplar clones. Our purpose was not only to derive adequate model systems of high predictive abilities, but also to enable flexibility in model implementation by considering different input variables (i.e. either total tree height or mean stand/stock height). These systems of models were rigorously examined using the set of goodness-of-fit criteria applied to the log-transformed model forms as well as to the back-transformed prediction data and via cross-validation (Tables 2-4). We finally obtained three systems of biomass prediction models that meet all predefined selection criteria (Tables 2-4).

Model system M1, based on both stand and tree height, yielded the smallest error values and captured the largest proportion of the biomass variation (Table 2), but tendency to include redundant parameters (PRSE statistic in Table 3) and predictors (Condition number in Table 2) should be admitted. The system of models M2 based on tree height yielded better goodness-of-fit estimates than system M3, which uses the mean stand height (Tables 2, 4, Figure 1). Model formulations based on the principle tree dimensions diameter at breast height and total height, and the stand/stock mean height quantified the poplar stem mass with high level of precision (Tables 2-4). Allometric models for branches also produced unbiased estimates and a negligible percentage of outliers was recorded (Table 2), but notable prediction errors and amount of variation around the main trend were still present (Table 4), which deduced poorer fits for branch than for stem biomass. This flaw was not manifested in the total lignified biomass prediction (Tables 2, 4, Figure 1) that can be ascribed to the significantly lower proportion of branches (around 15% on average) from the total tree dendromass (Table 1). Both mean errors and error variances estimated for prediction and validation data yielded similar values and the model efficiency criterion attained values close to the ideal nil value, particularly for the stem and total woody biomass (Table 4).

Table 3 Model systems for the aboveground dendromass compartments of hybrid black poplars: parameter estimates

Model	Parameter	a_0	a_1	b_0	b_1	b_2	b_3
M1	Estimate	-5.9091	2.0815	-6.2851	3.5147	5.5404	0.0106
	SE	0.0883	0.0442	0.1518	0.0809	0.3893	0.0030
	PRSE %[a]	1.49	2.12	2.42	2.30	7.03	27.95
M2	Estimate	-5.9503	2.1381	0.7613	0.4368	-6.4696	
	SE	0.0953	0.0472	0.0832	0.0104	0.2158	
	PRSE %	1.60	2.21	10.93	2.39	3.34	
M3	Estimate	-5.7459		-2.7902	0.4043	1.2675	
	SE	0.0530		0.1051	0.0266	0.1074	
	PRSE %	0.92		3.77	6.59	8.47	

Note. Abbreviations: *SE* - standard error, *PRSE*% - Parameter Relative Standard Error (%), *PRSE* = 100 x *SE*/|parameter|. *PRSE*% was defined as a criterion for stability of parameter estimate and must obtain values below 30%.

Table 4 Model systems for the aboveground dendromass compartments of hybrid black poplars: model precision at original (back-transformed) scale and cross-validation [a]

Model	Tree part	CF	Mean error, (kg) [b]	MARE (%)	ME	Prediction data set [c]		Validation data set	
						Mean error	Error variance	Mean error	Error variance
M1	w_s	0.99	2.45 x 10^{-15}	11.5	0.03	0.007	0.022	-0.006	0.025
	w_b	1.06	8.45 x 10^{-16}	69.8	0.14	-0.011	0.500	0.015	0.503
	w_t		3.13 x 10^{-15}	13.3	0.03	-0.008	0.031	0.009	0.033
M2	w_s	0.96	-8.34 x 10^{-16}	13.4	0.02	0.007	0.027	-0.010	0.029
	w_b	1.02	-1.02 x 10^{-15}	71.5	0.15	0.043	0.535	-0.046	0.536
	w_t		-2.13 x 10^{-15}	14.4	0.02	-0.004	0.037	0.001	0.038
M3	w_s	0.95	1.73 x 10^{-15}	27.9	0.05	-0.015	0.114	0.013	0.122
	w_b	1.13	-1.42 x 10^{-15}	80.1	0.15	0.051	0.491	-0.052	0.487
	w_t		1.41 x 10^{-16}	25.3	0.03	-0.020	0.103	0.018	0.109

Note. [a] The cross-validation results are based on 1000 simulation runs and the model precision is estimated from the log-transformed data. [b] Mean errors are not significantly different form zero in all cases; [c] Validation data set consists of 20% randomly selected in each run observations, while the remaining 80% of the observations compose the prediction data set used to fit the models.

Abreviations. w_s - dry biomass of stem (kg); w_b - dry biomass of branches (kg); w_t - total woody biomass: stem + branches (kg); CF - correction factor; MARE - mean absolute relative error $MARE\% = \frac{1}{n}\Sigma\frac{|y_i - \hat{y}_i|}{y_i}100$; ME - model efficiency $ME = \frac{\Sigma(y_i - \hat{y}_i)^2}{\Sigma(y_i - \bar{y})^2}$, where $y_i, \hat{y}_i, \bar{y}$ represent observed, predicted and mean observed biomass values.

Discussion

The stem model forms derived here are products of power, exponential and composed functions (Table 2), which describe the pace of increase at which each of the principal dimensional variables contributes to the aboveground dendromass growth. Models M1 and M3 predict stem growth as a power function of tree height (M1) or mean stand height (M3), which is consistent with the notion of growth as a multiplicative process. Power-form models have been shown to provide also the most adequate fit for the aboveground poplar biomass in studies by other investigators: for *Populus deltoides* in India (Ajit et al. 2011), for various poplar hybrids cultivated in Sweden (Johansson & Karačić 2011), for *Populus trichocarpa* Torr. and Gray x *P. deltoides* Marsh. hybrid trees in British Colombia (Zabek & Prescott 2006), for *Populus tremula* in Germany and Sweden, and for *Populus trichocarpa* in Iceland (Ziannis et al. 2005). Our analyses showed that the allometric exponent of diameter in the stem biomass models of black poplar hybrids is not a constant, but a function of mean stand height (M1) or diameter itself (M2 and M3). In the stem models of M2 and M3 this exponent took on increasing values of threshold 1, attained at breast height diameter of around 10 cm and 12 cm, respectively, thus playing the role of a reduction factor for the small-sized trees, where the multiplier $dbh^{b_1 \text{h} dbh}$ obtains values lower than the *dbh* in the base (i.e. $dbh^{b_1 \text{h} dbh} < dbh$), and an expansion factor for the relatively larger trees, i.e. $dbh^{b_1 \text{h} dbh}$ >dbh for dbh above 10 and 12 cm, respectively. The exponential function of the ratio dbh/h^2 and the power function of tree height h^{b_1} in model system M1, on the other hand, present a reduction-expansion interaction in which the reduction term exp(h^2 *dbh*) compensates for thicker trees of the same height. The logarithmic biometry equation, of the specific case when height exponent equals one (for systems M1 and M2), and the constant form factor equation

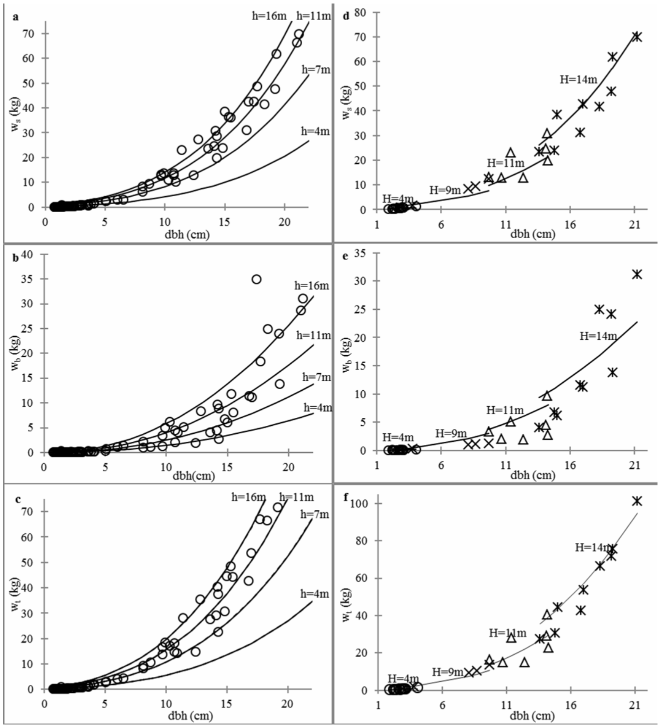

Figure 1 Observed vs. predicted biomass values according to breast height tree diameter (*dbh*, cm): a-b- c) by model system M2 for tree heights (*h*, m) 4, 7, 11 and 16m; d-e-f) by model system M3 for average stand heights (*H*, m) 4m (circles), 9m (crosses), 11m (triangles) and 14m (stars); a,d) - stem dry mass w_s (kg); b,e) branch dry mass w_b (kg); c,f) total dry dendromass w_t (kg).

(for system M3) were used to describe the biomass of poplar branches in this study (Table 2). They suggest that the product between the cross-sectional stem area and the sapling height (i.e. $dbh^2 h$, see also Tables 2 and 3) is a good predictor of branch biomass. However, considering the high variability in branch biomass data (Figure 1b), inclusion of additional independent variables such as crown length could be explored to increase the model accuracy.

In a study on *Nothofagus antarctica* tree allometry, Verónica at al. (2009) found that biomass allocation varied in relation to site quality following the optimal partitioning theory, which states that plants should allocate more biomass to the part of the plant that acquires the most limiting resource. Consequently, more biomass is allocated to the aboveground components in the best sites, while allocation to roots becomes more important in the worst sites. Our models also showed a positive correlation between site quality and aboveground dendromass growth. Branch biomass increased in proportion to the mean stand height in model systems M1 and M3, and site quality accounted even more strongly for the increase in stem biomass (e.g. in M3: $w^s \sim h^{1.3}$).

The breast height stem diameter is a principal tree dimensional variable and its inclusion in the allometric biomass models is implicit, especially for trees of decurrent crown form (sensu Burkhart & Tomé 2012). Some studies on tree allometry at juvenile stage, however, incorporate tree diameters at lower height above ground, such as 22 cm (Pontailler et al. 1997, Dillen et al. 2013, Verlinden et al. 2015), 30 cm (Walle et al. 2007) and 100 cm (Paris et al. 2011). Pontailler et al. (1997) even speculated that in young stands, diameter at breast height (1.30 m) is not a pertinent parameter because of the small size of the tree. Our study, like others on juvenile poplars (Felix et al. 2008, Fischer et al. 2011, Arora et al. 2014), supports the feasibility of measurement and use of breast height diameter in allometric biomass models of juvenile hybrid poplars for the simple reason that these are fast growing trees, and the height exceeds 1.3m even at one year of age. For single-stem trees, originated from cuttings, this parameter is also easier to measure than diameters at lower heights above ground. Our data showed that the average height of one-year-old cultivated black poplar stock exceeds 2 m (Table 1) and the percentage of trees that do not attain breast height is less than 5%. The dimensions and share of undersized plants suggest that omission of their contribution would not have a great impact on estimation of the total biomass yield from the plantation. Lignocellulosic poplar crops are usually managed by coppicing, which changes the tree form from decurrent to shrub-like (i.e. lacking a well-defined main stem). Consequently, instead of single-stem equations, multiple-stem-models might also be considered (Menéndez-Miguélez et al. 2013). Predictors needed for such models often include diameter at root collar instead of diameter at breast height (e.g. Ciuvăț et al. 2013), total height, number of stems and perhaps crown width (sensu Burkhart & Tomé 2012).

Conclusions

Three systems of compatible generic equations were derived in order to estimate stem, branch and total lignified biomass by considering different input variables to allow flexibility of model implementation. Equation system M1 proposes a stem biomass model based on tree and stand heights and stem diameter, and a model for branches including mean stand height and breast height diameter. Although this model displayed the best goodness-of-fit characteristics and predictive power, it is the most demanding in terms of input variables.

Model system M2 uses only the tree height and diameter and therefore is most relevant to dendromass determination in single trees or harvested saplings, while model M3 allows fast and sufficiently accurate biomass estimation of standing poplar stock, because it employs the average stand height and the individual tree diameters. All models are applicable to predict lignified aboveground biomass of juvenile *Populus deltoides* x *P. nigra* trees of diameter up to 21 cm and total height up to 16 m.

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