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CLONE-SPECIFIC BIOMETRIC MODELS FOR ABOVEGROUND DENDROMASS OF SINGLE-STEM AND COPPICED BLACK POPLAR CLONES DIFFERING IN AGE AND SPACING

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Abstract

The main objective of this study was to investigate the allometry of aboveground dendromass of both single-stem and coppiced black poplar hybrids at an early growth stage and to examine the potential of the variables age, growth space and number of sprouts as covariates in diameter-based (basal, d_0 or breast-height, *dbh*) power form models. Our investigation developed clone- and tree form-specific equations for the aboveground tree dendromass of the clones 'Agathe', 'I 45/51', 'NNDV' and 'BL', grown in a spacing trial in North-Western Bulgaria. All equations, which were derived as the best per clone×tree form combination, revealed high accuracy and predictive power, except for the equation of coppiced 'Agathe' trees. The clone-specific aboveground dendromass models for single-stem saplings showed higher goodness-of-fit than those of the coppices, where more significant dissimilarity of dendromass trends among the clones was also noticeable. Honer transformed variable model was the most adequate to describe monostem 'Agathe' and 'BL' biomass, while the simple *dbh*-based allometric equation was selected for monostem 'NNDV'. A d_0-based allometric model, in which the slope parameter was expanded by a power function of tree age predicted best the dendromass of the single-stem 'I 45/51'saplings. All models derived for the coppiced poplars included the number of sprouts as a second predictor variable. The clone-specific dendromass models, which possessed the higher goodness-of-fit within each tree form category, manifested also significantly improved prediction power as compared to the generic dendromass models for black poplar hybrids.

Key words: allometric models, biomass equations, Euro-American poplars, Nelder wheel design, *Populus deltoides* × *P. nigra*, short-rotation plantations.

Introduction

Biomass utilization for energy was established as a priority in Bulgaria through the National long-term strategy promoting biomass usage in the period 2008–2020 (Ministry… 2008), and wood was recognized as one of the main sources of biomass. Two principal dendromass suppliers have been identified: the remains from timber harvesting and wood-processing industry, and short-rotation crops from fast-growing tree species. The latter is given higher priority in Europe (Ericsson and Nilsson 2006). Bulgarian forests comprise a range of fast-growing species and genotypes, appropriate for short-rotation crops. Comprehensive research has been

carried out (Kolarov 1974; Tsanov 1986; Krastanov et al. 2004a, b; Tsakov 2009), and intensive plantations of selected poplar and willow clones, and black locust progenies have been established, mainly for timber and cellulose production.

Cultivation of short-rotation crops usually involves estimation of the total lignified biomass production, which is based on individual plant mass and plantation density. Tree biomass has been found to vary with species, genotype, population density, growth stage, management, topography and site characteristics (Sileshi 2014), and therefore generic models with multiple predictors are often preferred for quantifying biomass at larger scales. Biologically plausible and statistically sound generalized biometric models have been developed (Stankova et al. 2015, 2016) for estimation of dendromass and aboveground biomass of juvenile black poplar hybrids (*Populus deltoides* × *P. nigra*), traditionally cultivated for timber and cellulose production, using the breast height tree diameter, total tree and mean stand heights as predictor variables.

Some of the hybrid black poplar clones (*Populus deltoides* × *P. nigra*) are described as having thin branches ('I 45/51', 'Agathe', 'Luisa Avanzo', 'BL'), while thicker branches are characteristic of other clones (e.g. 'I 214', 'NNDV') (Tsanov and 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 age (Bond-Lamberty et al. 2002, Porté et al. 2002, Shaiek et al. 2011) and stand density (*sensu* Burkhart and Tomé 2012). The level of model generalization, when investigated, is usually determined by analysis of co-variance (ANCOVA), which either leads to model differentiation according to the significant covariates (Arevalo et al. 2007; Paul et al. 2013a, b) or to inclusion of these covariates as additional predictors in the models (Bond-Lamberty et al. 2002).

Biomass models for aboveground compartments of individual trees commonly utilize two principle tree dimensions as predictor variables: diameter at breast height (*dbh*, cm) and total tree height (*h*, m) (Clutter et al. 1983, Burkhart and Tomé 2012), but the change of the tree form to shrub-like, which is done by coppicing, suggests that 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 the breast-height diameter, total height, number of stems and perhaps crown width (*sensu* Burkhart and Tomé 2012).

Energy crops have been defined as short-rotation, high-density systems of selected genotypes grown under specific cultural regimes (Ceulemans and Deraedt 1999). Planting densities ranging from 2500 up to 100,000–300,000 plants per hectare have been investigated (DeBell et al. 1993), but the density range most often studied spans from 5000 to 40,000 stems per hectare (Cañellas et al. 2012). Ceulemans and 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. An experimental plantation was established in the spring of 2013 in North-Western Bulgaria using the Nelder wheel design with 4 hybrid black poplar clones and 11 nearly-square spacings, which accounted for initial densities

from 870 to 10,000 saplings per hectare. It was exposed to consecutive partial coppicing in 2014 and 2015. The experiment was designed to study the effect of genotype, spacing and rotation length on the biomass production. The main objective of this study was to examine the potential of variables age, growth space and number of sprouts as biomass predictors and to develop clone- and tree form-specific models for aboveground tree dendromass of investigated black poplar hybrids.

Materials and Methods

Experimental plantation and data collection

The experimental plantation was established in the spring of 2013 on the territory of Galovo nursery of Oryahovo Forest Range in North-Western Bulgaria (43º39´48.31˝ N, 24º05´44.11˝ E). The nursery is situated in the valley of Danube at altitude 25 m a.s.l. The climate is temperate continental, with average annual temperature 11.5–12 °C and average amount of annual precipitations of 515−630 mm. The soil is Haplic Kastanozem of high bulk density, low nitrogen, but high phosphorus and potassium content, and is poorly stocked with soil organic matter (Kaveko … 2006). The level of the underground water is close to the surface, the growth period lasts 6–7 months, with summer maximum of the precipitations, which provide conditions relatively favourable for poplar cultivation. The Nelder wheel experimental design (Nelder 1962, Namkoong 1965) was adopted with 4 hybrid black poplar (*Populus deltoides* × *P. nigra*) clones and 11 nearly-square spacings ranging from 1.0 to 11.5 m^2 (Fig. 1, Table 1). The clones were arranged in alternating spokes, grouped in sectors by 8, which were separated by two border spokes of the clone 'Panonia' (Fig. 1). Planting densities varied along the spokes, forming 13 concentric circumferences, with the innermost and the outermost circumferences playing the role of borders. Standard hardwood cuttings (18–20 cm) were used for plantation establishment and due to the limited cultivation activities the rooting rate was low and the percentage of under-sized saplings was high at the end of the first growth period. In accordance with the requirement of this specific design, adapted to study the genotype- and density-dependent tree growth (Namkoong 1965), replacement of the plants shorter than 1.3 m and replanting of the empty planting spots were done during the winter of 2013–2014 with standard 1-year-old saplings from the same clones, according to the scheme. The saplings of eight spokes (12–19) were coppiced in the same winter. Data collection took place in the autumn of 2014 and in 2015 by measuring of all trees from 2 sectors (16 spokes) each time. The trees of spokes 12–19 and 22–29 were harvested in 2014 and provided dendromass data from 2-year-old single-stem plants (spokes 22–29) and from coppiced plants of 2-year-old roots and 1-year-old shoots (spokes 12–19). Sampling of spokes 22–29 and 32–39 was done after the third growth period in 2015, which assured leafless biomass data from 3-year-old single-stem saplings (spokes 32–39) and from coppiced plants of 3-year-old roots and 1-year-old shoots (spokes 22–29) (Fig. 1, Table 1).

Each sample tree was cut to the ground at 5 cm maximum stump height. Stem length (to the nearest 1.0 cm), basal and breast-height tree diameters (to the nearest 0.1 cm) were measured for the single-

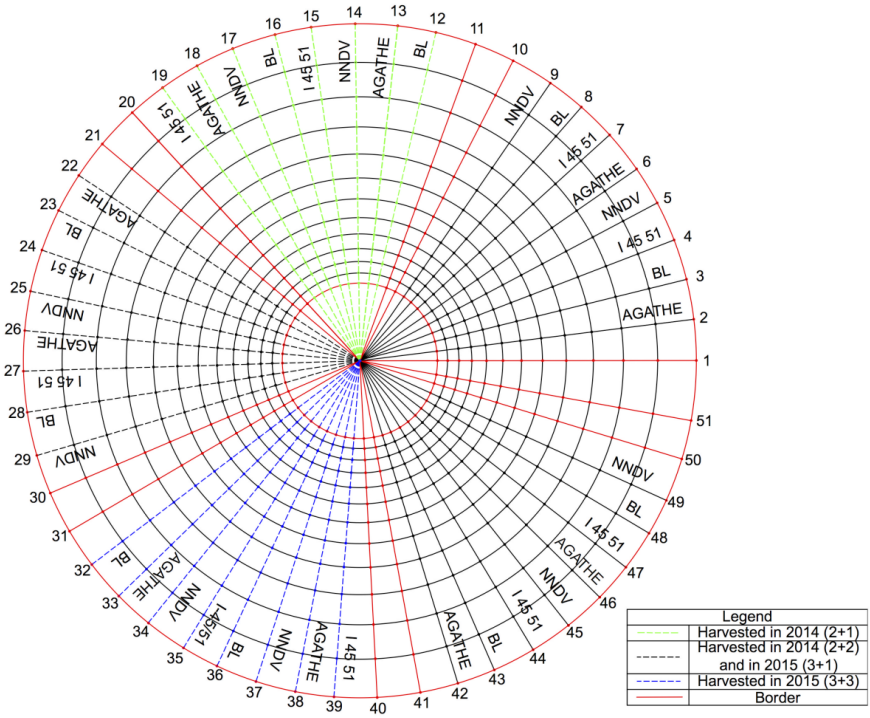

Fig. 1. Design of the experimental plantation.

stem saplings, while length, basal and breast-height diameters of the main stem and the number of stems were determined for the coppiced plants. The stems and the branches of each tree were separated and weighted *in situ*, to the nearest 0.005 kg. One stem and 1 branch samples (of around 100–200 g each) per tree were obtained from 3 saplings along each spoke. The collected woody parts were cut into 10–12 cm-long pieces, a size appropriate for oven-drying, and the fresh weight of all samples was measured in the field. They were packed in paper bags, transported to the laboratory and oven-dried at 105 °C to constant weight, which was measured to the nearest 0.001 kg. Proportions of dry to fresh weight were estimated for all samples. For each tree fraction (stem or branches) separately, these proportions were averaged from the respective samples obtained within the spoke. The calculated mean dry mass proportions were used to estimate the dry mass of the entire fractions of each tree in the spoke, using the respective fresh weights measured in the field. All allometric models derived in this study refer to the dry weight of aboveground woody fractions of the individual saplings.

Model development

We developed allometric models for estimation of the total tree dendromass (stem+branches), differentiated by clone and tree form (single-stem vs. coppiced).

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

Clone	Root age +stem age	Number of trees	[a] Spacing, m^2	[b] d_0, cm	[b] *dbh*, cm	[b] *h*, m	[b] *w*, kg	[b] Number of stems
Agathe	2+1	15		3.7 (2.0–5.6)	1.9 (1.0–3.1)	3.5 (2.2–4.9)	0.649 (0.095–2.122)	3 (1–5)
Agathe	2+2	21		3.5 (2.6–7.0)	2.1 (1.6–3.5)	3.7 (3.0–4.8)	0.576 (0.272–1.901)	1
Agathe	3+1	17	1.0	3.2 (1.9–4.5)	1.9 (0.9–3.1)	3.5 (2.0–4.6)	0.676 (0.152–1.691)	3 (1–10)
Agathe	3+3	22	1.3	6.3 (3.5–9.9)	4.3 (2.5–7.0)	5.8 (3.5–7.7)	2.961 (0.572–7.697)	1
BL	2+1	13	1.6	4.2 (2.6–6.3)	2.3 (1.4–2.9)	3.8 (2.7–4.6)	0.978 (0.234–1.993)	3 (1–5)
BL	2+2	22	2.1	4.6 (2.6–8.7)	2.6 (1.5–4.7)	4.0 (3.0–5.7)	0.943 (0.242–2.888)	1
BL	3+1	21	2.7	3.1 (1.3–9.3)	1.6 (0.6–2.3)	3.1 (1.7–4.0)	0.591 (0.050–1.509)	3 (1–12)
BL	3+3	22	3.4	6.3 (2.8–9.7)	4.2 (1.9–7.0)	5.7 (3.5–7.0)	2.508 (0.311–6.968)	1
I 45/51	2+1	13	4.3	4.1 (2.6–6.7)	2.2 (1.2–4.0)	3.1 (2.1–4.0)	0.725 (0.189–1.875)	3 (1–5)
I 45/51	2+2	21	5.5	3.6 (2.6–6.6)	2.2 (1.4–3.4)	3.2 (2.5–4.2)	0.482 (0.246–1.327)	1
I 45/51	3+1	17	7.1	3.4 (1.4–5.3)	1.9 (0.6–2.9)	3.0 (1.5–3.9)	0.613 (0.049–1.407)	2 (1–13)
I 45/51	3+3	22	9.0	5.8 (4.1–8.1)	4.0 (2.6–5.9)	4.9 (2.5–6.3)	2.144 (0.728–3.965)	1
NNDV	2+1	16	11.5	3.8 (3.0–4.9)	2.3 (1.4–3.5)	3.9 (3.1–4.6)	0.881 (0.274–1.479)	4 (1–6)
NNDV	2+2	19		3.9 (2.4–5.5)	2.2 (1.5–3.1)	3.8 (3.1–4.7)	0.665 (0.274–1.360)	1
NNDV	3+1	20		2.8 (1.6–3.8)	1.7 (0.6–2.4)	3.4 (1.6–4.2)	0.677 (0.059–1.766)	3 (1–9)
NNDV	3+3	22		6.1 (3.7–8.7)	4.2 (2.3–5.8)	5.8 (4.5–7.4)	2.449 (0.801–5.297)	1

Abbreviations: *dbh* – breast-height tree diameter; d_0 – basal tree diameter; *h* – total tree height; *w* – dry weight of the aboveground tree dendromass. Note: [a] – The planting schemes are presented in all Clone-Age combinations (columns 1 and 2); [b] – Mean and minimum – maximum variable values in brackets are presented.

In regard with the number of observations per clone-tree form combination (Table 1), we restricted the models to one- and two-predictor-equations and considered either the basal (d_0, cm) or the breast height tree diameter (*dbh*, cm) as the principal predictor.

We used the power function of diameter (either basal or breast height), which is known as the allometric equation (Huxley 1972) and which is linearized in the log-transformed form, and performed analysis of covariance (ANCOVA) to test the factors spacing, age (root age in the case of the coppiced plants) and number of sprouts (for the coppiced plants) for inclusion in the model as predictor variables. In case of proven significant influence of the covariate on the intercept and/or the slope of the allometric equation, we tested the model with the respective functional components expressed as linear or power function of the covariate. The superiority of the expanded model forms to the simple allometric equations was further assessed

by the extra sum of squares method and χ^2-test of Lakkis and Jones (Barrio-Anta et al. 2006, Picard et al. 2012). In addition, we examined 5 principal biometric models, based on tree diameter (basal or breast-height) and total tree height, which are used to model tree volume and biomass: combined variable, constant form factor, logarithmic, generalized logarithmic and Honer transformed variable (Clutter et al. 1983, Burkhart and Tomé 2012).

Prior to the analyses, we excluded the measurements of the trees, which are adjacent to missing plants and for which the available spacing is compromised and does not correspond to the design. All regression models tested were fitted in log-transformed form to the logarithm of total tree dendromass. The goodness-of-fit of the examined models was assessed by a set of nine criteria for adequacy (details are shown in the footnotes of Tables 4 and 5), e.g. tests for normality, homoscedasticity, unbiasedness, derived from Gadow and Hui (1999), Parresol (1999), Picard et al. (2012) and Sileshi (2014), and according to the requirement for biologically-logical model behaviour, by the adjusted coefficient of determination ($R_{adj.}$), the root mean squared error (RMSE) and Akaike information criterion (AIC), which were used also to select the best models. To convert the predicted values to arithmetic, untransformed units, the ratio correction for bias (Snowdon 1991) was applied (formula shown in the footnote of Table 4). Finally, we compared the newly derived clone and tree form-specific models with the generic biomass models for aboveground dendromass of hybrid black poplars, derived by Stankova et al. (2016), employing the estimation of model efficiency (*ME*) and the absolute relative error (*ARE*%) (formulae shown in the footnote of Table 6). Model efficiency (*ME*) is a relative measure of model performance analogous to the coefficient of determination, but of ideal value equal to zero (Gadow and Hui 1999). Mean value, 25th, 50th and 75th percentiles of *ARE*% were estimated, which indicate the range and the magnitude of prediction errors relative to predicted dendromass. In addition, we tested whether the biomass values predicted by the generic and the specific models differ significantly from each other by paired-samples non-parametric test (Sign test).

Results

With a few exceptions, the investigated covariates did not affect concomitantly the slope and the intercept of the allometric models, but either of them (Table 2). The ANCOVA results for the factor 'spacing' were ambiguous, while age was proven as a significant covariate of the d_0-based allometric models of all single-stem clones, but did not influence significantly the allometric equation parameters of coppiced poplars (except for the intercept of d_0-based model of 'Agathe'), where it corresponded to root age alone. A strong covariate effect in this case was manifested by the stem number, which was found to significantly contribute for the improved predictability of both types of allometric models of all coppiced clones (Table 2). The ANCOVA indicated stronger differentiation of the dendromass allometric models according to alternative tree forms than by clone.

One-predictor allometric models did not prove adequate for all clones and tree forms. Expanded models of d_0-based allometric equation were derived for 4 clone×tree form combinations, while allometric equation of *dbh* was only expanded

Table 2. Tests for spacing, age and number of stems as covariates of tree diameter in estimating aboveground tree dendromass.

Type of plant	Model		Significant covariates according to clone			
			Agathe	BL	I 45/51	NNDV
Single stem	$\ln w = b_0 + b_1 \ln dbh$	Intercept b_0	-	-	Age	Spacing
		Slope b_1	-	-	Age	Spacing
		Slope b_1 and Intercept b_0	-	-	-	-
	$\ln w = b_0 + b_1 \ln d_0$	Intercept b_0	Spacing Age	Spacing Age	Age	Spacing Age
		Slope b_1	Spacing Age	Spacing Age	Age	Spacing Age
		Slope b_1 and Intercept b_0	-	-	-	-
Coppiced	$\ln w = b_0 + b_1 \ln dbh$	Intercept b_0	Stem number	Spacing Stem number	Spacing Stem number	Spacing Stem number
		Slope b_1	Stem number	Spacing Stem number	-	Spacing Stem number
		Slope b_1 and Intercept b_0	-	-	Spacing	Stem number
	$\ln w = b_0 + b_1 \ln d_0$	Intercept b_0	Age Stem number	Stem number	Stem number	Spacing Stem number
		Slope b_1	Stem number	Stem number	Stem number	Spacing Stem number
		Slope b_1 and Intercept b_0	-	Stem number	Stem number	Stem number

Abbreviations: *dbh* – breast-height tree diameter; d_0 – basal tree diameter.

with the stem number for coppiced 'BL' saplings dendromass (Table 3). The two-predictor formulations in these cases proved to be significantly better than the reduced model forms, which was indicated by the Extra sum of squares and the Lakkis-Jones tests. Two-predictor models including basal diameter and age were mainly derived for the single-stem black poplar trees and adequate dependencies of height and diameter were also developed for all clones. Dendromass models, which included the number of sprouts as an independent variable, were developed for all coppiced clones that confirmed its predictive power (Table 3). Two-predictor dendromass models involving spacing were suggested for the single-stem 'Agathe' and for the coppiced 'BL' and 'NNDV' (Table 3).

Clone-specific aboveground dendromass models derived for the single-stem saplings showed higher goodness-of-fit than those of the coppices (Table 4), where more significant dissimilarity of dendromass trends among the clones was also noticeable (Fig. 2).

All equations, which were derived as the best per clone×tree form combination, revealed high accuracy and predictive power, except that for coppiced 'Agathe' trees (Tables 4 and 6). Honer transformed

Table 3. Aboveground dendromass models for the investigated poplar clones.

Clone	Single-stem trees		Coppiced trees	
Agathe	**R**	$\ln w = b_0 + b_1 \ln d_0$	**R**	$\ln w = b_0 + b_1 \ln d_0$
	E1	$\ln w = b_0 Spacing^{b_1} + b_2 \ln d_0$	**E, B**	$\ln w = b_0 + b_1 SN \ln d_0$
	E2	$\ln w = b_2 + b_0 Spacing^{b_1} \ln d_0$		$\ln w = b_0 + b_1 \ln SN \ln d_0$
	E3	$\ln w = b_0 + b_1 \ln Spacing + b_2 \ln d_0$		$\ln w = b_0 + Age + b_1 \ln d_0$
	E4	$\ln w = b_0 + b_1 Age + b_2 \ln d_0$		
	E5	$\ln w = b_0 Age^{b_1} + b_2 \ln d_0$		
	E6	$\ln w = b_0 + (b_1 + b_2 Age) \ln d_0$		
	E7	$\ln w = b_0 + (b_1 Age^{b_2}) \ln d_0$		
	E8	$\ln w = b_0 + b_1 \exp(Age) + b_2 \ln d_0$		
	E9	$\ln w = b_0 + b_1 \ln Age + b_2 \ln d_0$		
		$\ln w = b_0 + b_1 \exp(Age) \ln d_0$		
		$\ln w = b_0 + b_1 \ln Age \ln d_0$		
		$\ln w = b_0 + b_1 \ln dbh$		
	B	$\ln w = \ln dbh^2 - \ln(b_0 + b_1 / h)$		
BL		$\ln w = b_0 + b_1 \ln dbh$	**R**	$\ln w = b_0 + b_1 \ln dbh$
		$\ln w = \ln(b_0 + b_1 \ln dbh^2)$	**E1**	$\ln w = b_0 + b_1 SN + b_2 \ln dbh$
	B	$\ln w = \ln dbh^2 - \ln(b_0 + b_1 / h)$	**E2, B**	$\ln w = b_0 SN^{b_1} + b_2 \ln dbh$
			E3	$\ln w = b_0 + (b_1 + b_2 SN) \ln dbh$
				$\ln w = b_0 SN^{b_1} \ln dbh$
			E4	$\ln w = b_0 + b_1 \ln SN + b_2 \ln dbh$
			E5	$\ln w = b_0 Spacing + b_2 \ln dbh$
				$\ln w = b_0 + Spacing^{b_1} \ln dbh$
			E6	$\ln w = b_0 + b_1 \ln Spacing + b_2 \ln dbh$
				$\ln w = b_0 + b_1 \ln d_0$
I 45/51		$\ln w = b_0 + b_1 \ln d_0 + b_2 h$	**R**	$\ln w = b_0 + b_1 \ln d_0$

		$\ln w = \ln b_0 + 2\ln d_0 + \ln h$	**E1, B**	$\ln w = b_0 + b_1 SN + b_2 \ln d_0$
		$\ln w = b_0 + b_1 Age \ln d_0$	**E2**	$\ln w = b_0 + b_1 \exp SN + b_2 \ln d_0$
	B	$\ln w = b_0 + Age^{b_1} \ln d_0$		$\ln w = \ln b_0 + 2\ln d_0 + \ln h$
		$\ln w = b_0 + b_1 \ln Age + b_2 \ln d_0$		$\ln w = b_0 + SN^{b_1} \ln dbh$
		$\ln w = b_0 + b_1 \exp Age \ln d_0$		
		$\ln w = b_0 + b_1 \ln Age \ln d_0$		
		$\ln w = b_0 + Age + b_1 \ln d_0$		
NNDV	**B**	$\ln w = b_0 + b_1 \ln dbh$		$\ln w = b_0 + b_1 SN + b_2 \ln dbh$
	R	$\ln w = b_0 + b_1 \ln d_0$	**B**	$\ln w = \ln(b_0 + b_1 SN) + b_2 \ln dbh$
	E1	$\ln w = b_0 + b_1 Age + b_2 \ln d_0$		$\ln w = b_0 SN^{b_1} + b_2 \ln dbh$
	E2	$\ln w = b_0 Age^{b_1} + b_2 \ln d_0$		$\ln w = b_0 + SN^{b_1} \ln dbh$
	E3	$\ln w = b_0 + (b_1 + b_2 Age) \ln d_0$		$\ln w = b_0 + b_1 SN + b_2 \ln dbh$
	E4	$\ln w = b_0 + b_1 \exp Age + b_2 \ln d_0$		$\ln w = \ln(b_0 + b_1 Spacing) + b_2 \ln dbh$
	E5	$\ln w = b_0 + b_1 \ln Age + b_2 \ln d_0$		$\ln w = b_0 + b_1 Spacing^{b_2} \ln dbh$
		$\ln w = b_0 + Age^{b_1} \ln d_0$		$\ln w = b_0 + b_1 \ln Spacing \ln dbh$
		$\ln w = b_0 + b_1 \exp Age \ln d_0$		$\ln w = \ln b_0 + 2\ln d_0 + \ln h$
		$\ln w = b_0 + b_1 \ln Age \ln d_0$		
		$\ln w = \ln b_0 + 2\ln d_0 + \ln h$		

Abbreviations: **E** – expanded model; **R** – reduced model; **B** – the best model for the clone; *SN* – number of stems; *dbh* − breast-height tree diameter, cm; d_0 – basal tree diameter, cm; *h* − total tree height, m; *w* – dry weight of the aboveground tree dendromass, kg.

variable model was the most adequate to describe the biomass of the monostem 'Agathe' and 'BL', while the simple *dbh*-based allometric equation was selected for 'NNDV' clone. A d_0-based allometric model, in which the slope parameter was expanded by a power function of tree age, predicted best the dendromass of single-stem 'I 45/51' saplings (Tables 4 and 5, Fig. 2a). All best models for the coppiced poplars included the number of sprouts as a second predictor variable (Table 4, Fig. 3). The breast-height diameter was principal predictor in the equations of 'BL' and 'NNDV' clones, which intercepts were expanded with power ('BL') or linear ('NNDV') functions of stem number. Expanded forms of d_0-based allometric equation were derived for the coppiced 'Agathe' and 'I 45/51' where linear

Table 4. Adequacy tests for the best aboveground dendromass models.

Type of plant	Clone	Model	CF	R^2adj	RMSE	AIC	Mean error [a]	A-D [b]	B-P [b]	Model bias [c]	CN [d]	SR (%) [e]	LP (%) [e]	IP (%) [e]
Single stem	Agathe	$\ln w = \ln dbh^2 - \ln(b_0 + b_1/h)$	1.00	0.980	0.145	-164.0	0	0.343	0.122	0.068	7.26	4.65	0	2.33
	BL	$\ln w = \ln dbh^2 - \ln(b_0 + b_1/h)$	0.99	0.990	0.088	-211.7	0	0.332	2.123	0.287	2.24	2.27	2.27	4.55
	I 45/51	$\ln w = b_0 + Age^{b_1} \ln d_0$	1.03	0.936	0.222	-127.4	5.10×10^{-11}	0.522	5.748	1.79×10^{-4}	4.28	4.65	0	2.33
	NNDV	$\ln w = b_0 + b_1 \ln dbh$	1.01	0.970	0.139	159.9	0	0.498	1.036	4.72×10^{-27}	6.02	2.44	2.44	2.44
Coppiced	Agathe	$\ln w = b_0 + b_1 SN \ln d_0$	1.09	0.402	0.518	-40.2	0	0.241	3.059	1.62×10^{-28}	3.03	6.25	3.13	9.38
	BL	$\ln w = b_0 SN^{b_1} + b_2 \ln dbh$	1.02	0.936	0.216	-101.4	-1.57×10^{-4}	0.620	0.197	1.42×10^{-5}	4.00	5.88	5.88	8.82
	I 45/51	$\ln w = b_0 + b_1 SN + b_2 \ln d_0$	1.02	0.893	0.285	-72.5	0	0.333	2.318	0.078	9.05	10	6.67	10
	NNDV	$\ln w = \ln(b_0 + b_1 SN) + b_2 \ln dbh$	1.01	0.870	0.267	-92.3	0	0.399	4.934	4.46×10^{-5}	4.59	2.78	5.56	5.56

Note: [a] – Mean errors are not significantly different form 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 multicollinearity and must obtain values below 30; [e] – Outliers in the response variable are assessed by the percentage of Studentised residuals $\in$[-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 %. Abbreviations: *dbh* – breast-height tree diameter, cm; d_0 – basal tree diameter, cm; *h* – total tree height, m; *w* – dry weight of the aboveground tree endromass, kg; *CN* – condition number; *CF* – bias-correcting coefficient: $CF = \frac{\sum y_i}{\sum \exp(\overline{\ln y_i})}$ and $\hat{y}_i = CF \exp(\overline{\ln y_i})$, where $y_i, \hat{y}_i$ are experimental and predicted biomass values of the *i*-th measurement, and $\overline{\ln y_i}$ is the predicted value of the log-transformed biomass of the *i*-th measurement, RMSE – root mean squared error, kg; R^2_{adj} – adjusted coefficient of determination; AIC – Akaike Information Criterion; A-D – Anderson-Darling test statistics; B-P – Breusch-Pagan test statistics; SR – Studentised residuals; LP – Leverage points; IP – Influential points.

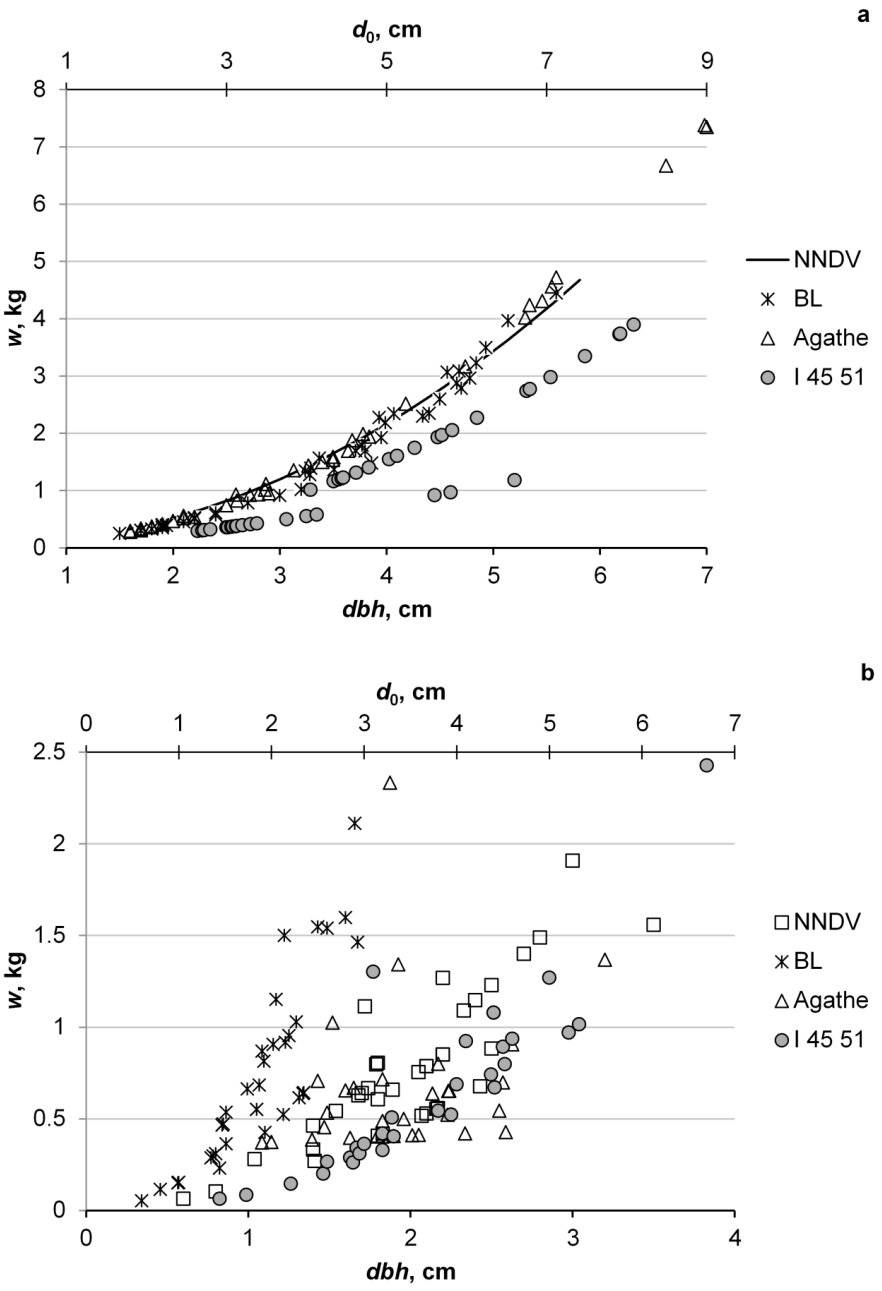

Fig. 2. Predicted aboveground dendromass by clone: a – Single-stem trees; b – Coppiced trees.

Abbreviations: *dbh* – breast-height tree diameter, cm; d_0 – basal tree diameter, cm; *w* – dry weight of the aboveground tree dendromass, kg.

Table 5. Parameter estimates for the best aboveground dendromass models.

Type of plant	Clone	Parameter	b_0	b_1	b_2
Single stem	Agathe	Estimate	4.695	14.451	
		SE	0.639	2.901	
		PRSE % [a]	13.61	20.08	
	BL	Estimate	4.808	16.102	
		SE	0.436	2.046	
		PRSE %	9.06	12.70	
	I 45/51	Estimate	-2.731	0.605	
		SE	0.076	0.027	
		PRSE %	2.80	4.46	
	NNDV	Estimate	-2.100	2.063	
		SE	0.067	0.057	
		PRSE %	3.19	2.78	
Coppiced	Agathe	Estimate	-1.188	0.164	
		SE	0.154	0.035	
		PRSE %	12.97	12.41	
	BL	Estimate	-2.259	-0.250	2.101
		SE	0.093	0.036	0.104
		PRSE %	4.13	14.38	4.93
	I 45/51	Estimate	-3.824	0.120	2.212
		SE	0.209	0.023	0.159
		PRSE %	5.45	19.07	7.21
	NNDV	Estimate	0.112	0.036	1.689
		SE	0.017	0.008	0.135
		PRSE %	15.38	20.74	7.97

Abbreviations: SE – standard error; PRSE % – Parameter Relative Standard Error, %; PRSE = 100×SE/|parameter|.
Note: [a] PRSE % was defined as a criterion for stability of parameter estimate and must obtain values below 30 %.

function of the stem number was incorporated in the slope (‘Agathe’) or the intercept (‘I 45/51’) of the model (Tables 4 and 5, Fig. 2b).

The clone-specific dendromass models, which possessed the higher goodness-of-fit within each tree form category (monostem ’Agathe‘, ’BL‘ and multistem ’BL‘, ’I 45/51‘), manifested also significantly improved prediction power as compared to the generic dendromass models for black poplar hybrids (Table 6). In the assessment of single-stem aboveground dendromass, the generalized models revealed error range and model efficiency of very similar magnitude to that, estimated for the specific models. The new specific biometric models appeared most beneficial for the clone ‘BL’ regardless of its form (Table 6).

Discussion

The high stocking rate required for establishment of short-rotation crops can be achieved by either closely spaced monostem plantings or by coppicing; the priority to coppicing should be given when the average of mean annual increments of coppice harvests is greater than the maximum mean annual increment of single ro-

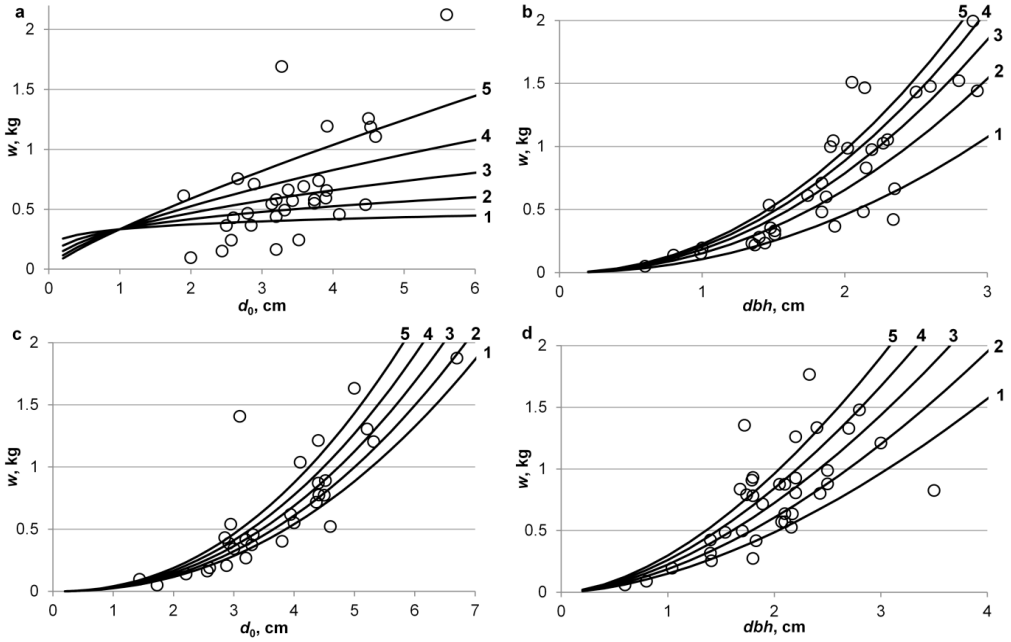

Fig. 3. Aboveground dendromass prediction trends for coppiced hybrid poplars according to tree diameter and number of sprouts (1, 2, 3, 4, 5): a – Agathe; b – BL; c – I 45/51; d – NNDV.

Abbreviations: *dbh* – breast-height tree diameter, cm; d_0 – basal tree diameter, cm; *w* – dry weight of the aboveground tree dendromass, kg.

tation (Ribeiro and Betters 1995). The investigated experimental plantation allows to study in parallel both single-stem and coppiced poplar saplings and we aimed at development of reliable clone-specific biometric relationships to enable fast estimation and comparison of aboveground dendromass productivity of particular genotypes. Plant biomass allometry studies have been conducted by either direct modeling of total tree biomass or by development of additive systems of equations for different plant compartments (Laureysens et al. 2005; Zianis et al. 2005; Fajman et al. 2009; Menéndez-Miguélez et al. 2013; Stankova et al. 2015, 2016). Our study developed clone-specific biometric models for aboveground tree dendromass assessment to address the need of fast, simple and easy calculation for practical purposes. The comparison with the previously derived generic additive models (Stankova et al. 2016) revealed that both model types were adequate for the single-stem juvenile poplars. As expected, the same manner of application of the generalized models to coppiced plants was not very appropriate since the resultant estimates reflected more the dendromass of the main sprout alone rather than the dry mass of the entire stool. Alternatively, the generic dendromass model can be applied individually to each shoot on the stump, but such calculation would be rather complicated and the breast-height diameter may not be an adequate predictor, because of the smaller size of secondary shoots.

Table 6. Comparison between specific and generic dendromass models.

Type of plant	Clone	Sign test statistic [a]	Generalized model					Specific model				
			ME	MARE %	Perc25	Perc50	Perc75	ME	MARE %	Perc25	Perc50	Perc75
Single stem	Agathe	10.5***	0.090	0.18	0.08	0.19	0.26	0.021	0.11	0.04	0.09	0.16
	BL	13.0**	0.098	0.14	0.05	0.15	0.20	0.024	0.07	0.03	0.05	0.11
	I 45/51	-1.5^{ns}	0.180	0.19	0.07	0.14	0.27	0.063	0.17	0.05	0.12	0.24
	NNDV	3.5^{ns}	0.121	0.13	0.03	0.11	0.21	0.050	0.12	0.06	0.11	0.16
Coppiced	Agathe	2.0^{ns}	0.712	0.32	0.12	0.33	0.47	0.566	0.48	0.12	0.31	0.55
	BL	21.0***	0.839	0.35	0.18	0.42	0.49	0.071	0.16	0.04	0.10	0.22
	I 45/51	4.5**	0.629	0.38	0.24	0.39	0.49	0.157	0.24	0.11	0.23	0.33
	NNDV	10.0^{ns}	0.978	0.32	0.17	0.32	0.46	0.410	0.21	0.08	0.15	0.34

Abbreviations: *ME* – model efficiency; $ME = \frac{\sum (y_i - \hat{y}_i)^2}{\sum (y_i - \bar{y})^2}$; *ARE*% – absolute relative error; $ARE\% = \frac{|y_i - \hat{y}_i|}{y_i} 100$, where $y_i, \hat{y}_i$ are experimental and predicted biomass values of the *i*-th measurement and $\bar{y}$ represents the mean observed biomass value; *MARE* % - mean absolute relative error; Perc25, Perc50 and Perc75 denote the 25th, 50th and 75th percentile of the absolute relative errors, respectively.

Note: [a] – the null hypothesis tests that the median of the paired differences distribution equals zero. Level of significance: *** - $P<0.001$, ** - $P<0.01$, ^{ns} – $P>0.05$.

The majority of the studies on coppiced plantations use the general allometric equation (Huxley 1972), by relating dry biomass weight of each individual shoot on the stump to a power function of its diameter at a certain height above ground and evaluate the total plant mass per stump or unit area by summing up the individual shoot weights (Laureysens et al. 2003, 2005; Paris et al. 2011; Ghaley and Porter 2014; Verlinden et al. 2015). Proe et al. (1999), on the other hand, employed as a predictor in their allometric equations the individual shoot basal area, while the sum of the basal areas of the sprouts on a stump was used in the models by Razakamanarivo et al. (2012). To provide a quick estimate of biomass by measuring only some stems in a stool, Menéndez-Miguélez et al. (2013) attempted in modeling the whole-stool dendromass of coppiced chestnut the same approach as our for coppiced poplars. The size (diameter and height) of the biggest shoot was not derived as a good predictor of coppiced chestnut plants in their study and they employed instead the mean

shoot diameter and the basal area of stool together with the number of sprouts on the stump (Menéndez-Miguélez et al. 2013). Diameter (basal or breast-height) of the principal sprout was proven as a good predictor of poplar dendromass at stump level in our study and the best biometric models including diameter and number of shoots explained more than 85 % of the variation in the stool biomass of 3 of the investigated clones. Ceulemans and Deraedt (1999) emphasized that there was a great deal of genotypic variation in the number of sprouts after coppicing and Laureysens et al. (2003) found significant correlation between the number of shoots and stool biomass. In an investigation on coppiced willows Bergkvist and Ledin (1998) also found strong correlation between biomass and number of shoots, but the authors pointed out that the variability in shoot number increased with age leading to decreased influence of the shoot number as a covariate. This finding suggests that the results of our study can be further extended and conclusions would be strengthened by inclusion of data for 2- and 3-year-old shoots.

Numerous studies investigate the influence of stand density on biomass production (*sensu* Cañellas et al. 2012), but very few address its effect on the biomass allometry. Our results on the influence of spacing as a predictor of aboveground dendromass were not unequivocal and significant relationships were established for two coppiced ('BL' and 'NNDV') and one single-stem ('Agathe') clones only. Although inclusion of the independent variable 'spacing' significantly improved the predictability of diameter-only equations, the two-predictor models based on the other tested covariates showed higher goodness-of-fit. In line with the allometry investigations of other species of monostem tree form (Bond-Lamberty et al. 2002, Porté et al. 2002, Shaiek et al. 2011), we also derived age-dependent dendromass models for the single-stem 'Agathe', 'I 45/51' and 'NNDV'. However, the biometric relationships of coppiced poplars in regard with various root-shoot age combinations is of particular interest and requires further investigation.

Conclusions

Clone-specific as well as the generalized allometric models applied to the particular poplar clones revealed high accuracy and predictive power in estimation of aboveground tree dendromass of individual stems. The whole-stump dendromass of coppiced poplars can be reliably assessed by employing models based on either basal ('Agathe', 'I 45/51') or breast-height ('BL', 'NNDV') diameter of the main sprout and the number of shoots per stump. Further investigation on the allometry of coppiced poplars is envisaged by inclusion of data for 2- and 3-year-old shoots and in regard with various root-shoot age combinations.

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