

ORIGINAL RESEARCH

The effects of cultivar and rotation length (5 vs. 10 years) on biomass production and sustainability of poplar (*Populus* spp.) bioenergy plantation

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Funding information

Funding for this research was provided by the Directorate General of the State Forests (Poland; projects no. 500 425, 500 468).

Abstract

Poplars (*Populus* spp.) managed in short rotation woody crop (SRWC) systems are considered very promising in terms of biomass production for energy purposes in a temperate zone. In this study, several gaps in knowledge regarding the selection of the plant material, cultivar-specific responses to coppicing and rotation length are addressed. Five- and 10-year rotation lengths were considered, with a focus on the sustainability of the plantation and the quantification of the biomass production of 10 commercially available hybrid poplar cultivars during two consecutive 5-year rotation cycles versus one 10-year rotation in northern Poland. The biomass production varied considerably among cultivars, ranging from 1.6 ('AF8') to 7.5 ('NE42') Mg ha⁻¹ year⁻¹ at the end of the first 5-year rotation, and 0.0 ('AF8')–5.4 ('Degrosso') Mg ha⁻¹ year⁻¹ in the second 5-year rotation, while in a single 10-year rotation, the mean annual increment (MAI) ranged from 1.0 ('AF8') to 15.1 ('NE42') Mg ha⁻¹ yr⁻¹. The 5-year rotation cycles negatively influenced the sustainability of the plantation due to the high mortality of stems and sprouts in the second 5-year coppice rotation. In the case of 5-year and longer rotations, replanting (not resprouting) after harvest may be a more advantageous practice for maximizing the regeneration. The 10-year rotation cycle allowed for enough development of the crown and root systems to produce sufficient basal area and height to achieve maximal MAI in the trees. The study revealed that an age ≥10 is a biologically optimal rotation age as the slope of MAI was equal/close to zero. This study further showed the crucial importance of testing cultivars before introducing them on a commercial scale and provided valuable information on poplar cultivars available to stakeholders in the biomass market.

KEYWORDS

biomass, coppice, cultivar, mean annual increment, NE42, *Populus* spp., rotation length, short rotation woody crops, sprouts

1 | INTRODUCTION

Interest in bioenergy has increased globally (Griffiths et al., 2019; Qin et al., 2018; Stolarski et al., 2020; Zhang et al., 2020). In 2019, the European Union (EU) updated its energy policy framework to include a transition from fossil fuels towards cleaner energy and deliver on the EU's Paris Agreement commitments for reducing greenhouse gas (GHG) emissions. The EU has set a target of 32% for renewable energy sources by 2030 (EU, 2018), with carbon neutrality to be achieved by 2050. Energy transition to reach these targets means that multiple fossil-free or emission-free solutions must grow substantially in the foreseeable future (Zappa et al., 2019). This will be challenging for Poland, which is an EU leader in hard coal mining (first place in the EU in 2018; Statistics Poland, 2020).

Up until now, solid biofuels have been the most important renewable energy source in the EU, achieving a 40.3% (69.3% in Poland) share in the structure of primary energy production from renewable sources in 2018 (Statistics Poland, 2020). Solid biofuels are obtained mainly from woody biomass of forestry and agricultural crops (Rosso et al., 2013). Another promising biomass source includes short rotation woody crop (SRWC) systems, based on short, clear-felling cycles (generally between 1 and 15 years) utilizing genetically superior planting material, and often relying on coppice regeneration (Griffiths et al., 2019; Dickmann, 2006). The production of biomass as feedstock for energy generation and industrial processes from SRWC plantations is still being developed in many countries in Europe (Afas et al., 2008; Dillen et al., 2013; Njakou Djomo et al., 2015; Stolarski et al., 2020; Verlinden et al., 2015), the USA and Canada (Clifton-Brown et al., 2019; Ghezehei et al., 2020; Zalesny & Headlee, 2015). Biomass is generally presumed to be carbon neutral, given that emissions from biomass combustion are compensated by plant regrowth (Ragauskas et al., 2006; Yan, 2018; Zeman & Keith, 2008). A recent analysis of the role of biomass in the reduction of fossil GHG emissions in the North European (including Poland) energy sector suggests the sustained importance of this source (Jåstad et al., 2020).

Poplar (*Populus* spp.) is one of the most promising genera in terms of biomass production for energy purposes in the temperate zone due to its high yield, low input requirements and maintenance of biodiversity (Nassi O Di Nasso et al., 2010; Zajączkowski, 2013). However, data on cultivar-specific biomass production and growth parameters are still largely absent. From a long-term perspective, the success of an SRWC depends on the choice of plant material (Vanbeveren & Ceulemans, 2018). The deployment of well adapted, that is, productive and resilient cultivars, is essential for the sustainability of plantations and biomass supply for the energy sector. Data of plant material are needed especially for the more recently released cultivars, over different rotation lengths and

cycles, in environmental conditions where future deployment is anticipated. Depending on the productivity of sites and climatic conditions, the production of the feedstock for bioenergy may generally require a different rotation length: shorter in warmer temperate climates, while longer rotation lengths may be more desirable in more northern geographical locations (Nordborg et al., 2018). Shorter rotation cycles allow for higher planting densities, and thus, higher biomass yields per unit land area and time (Dillen et al., 2013). Longer rotations, on the other hand, provide an opportunity to produce woody biomass of higher quality (Benomar et al., 2012; Rosso et al., 2013), thereby achieving greater energy efficiency (Nassi O Di Nasso et al., 2010), a more favourable carbon balance due to less intensive management (Smith et al., 2012) and resulting in a smaller environmental impact (Griffiths et al., 2019; Nassi O Di Nasso et al., 2010).

For many years, poplars have been selected mainly for single-stem growth and straight stem form in traditional breeding and selection programmes (Steenackers et al., 1996). As a result, several commercially available poplar cultivars may not tolerate frequent harvesting or short rotation cycles without a decrease in productivity or resprouting capacity (Dillen et al., 2013). Whether particular poplar cultivars are preferable for shorter rotations or for longer term applications, needs to be examined at particular sites or regions, before deployment on a commercial scale (Ghezehei et al., 2020).

Most poplars have vigorous regrowth after coppicing (Ceulemans et al., 1996; Stettler et al., 1996; Verlinden et al., 2015) with resprouting of five to 25 shoots per coppiced tree. Due to self-thinning, however, the number of sprouted shoots reduces significantly within a rotation (Ceulemans et al., 1996; Stettler et al., 1996; Vanbeveren & Ceulemans, 2018; Verlinden et al., 2015). Shoot mortality occurs mostly among the smallest shoots, in deference to the largest shoots, whose dominance increases. From a scientific point of view (understanding shoot population dynamics and biomass determinants), as well as from a practical perspective (yield and economic profitability of plantations), the effects of different rotations and cycle lengths on biomass production and shoot dynamics in different poplar cultivars need to be understood better.

In recent years, biomass production-related issues of poplars in SRWCs have been addressed in many studies (Afas et al., 2008; Benetka et al., 2014; Dillen et al., 2013; Ghezehei et al., 2015; Nassi O Di Nasso et al., 2010; Paris et al., 2011; Testa et al., 2014; Vanbeveren & Ceulemans, 2018; Verlinden et al., 2015; Volk et al., 2018; Yáñez et al., 2019). Although SRWC rotation lengths can last up to 15 years, the vast majority of research has considered very short rotations (1- to 3-year rotation cycles) and has covered a relatively short period in the lifespan of the plantation. In this study, several gaps in the knowledge regarding the selection of plant

material and rotation length (considering the rarely described 5- and 10-year rotations) in a temperate continental climate are addressed. Specifically, the study aimed to: (1) determine the productivity of various poplar cultivars selected in earlier breeding programmes for timber production versus new commercially available cultivars suitable for SRWC systems for commercial biomass production; (2) quantify the biomass production during two consecutive 5-year rotation cycles versus one 10-year rotation; and (3) identify the cultivar-specific responses in coppicing and its impact on productivity and survivability in northern Poland. These issues were addressed to provide landowners and other stakeholders with knowledge on sustainability and productivity of SRWC plantations, and thus the profitability of such investments, and to guide the most important silvicultural practices, including selection of cultivars and rotation length.

2 | MATERIALS AND METHODS

2.1 | Site description

The experiment was initiated in April 2010. The experimental site of the study was located in northern Poland (54°4'26"N, 20°30'4"E), near Lidzbark Warmiński. The long-term, average annual temperature is 8.0°C with an annual precipitation of 683 mm. During the study period, the lowest precipitation (below 600 mm) was recorded in 2013, 2014, 2015 and 2018, while in 2016 and 2017, total precipitation was the highest in the experiment, at 737 and 973 mm respectively (Figure 1).

The experimental area was established on post-agricultural land, and the soil conditions were relatively uniform throughout the site. In 2016, a detailed soil survey was carried out.

Based on the description of the soil profiles, the predominant soil type was classified as Cambisol (according to the World Reference Base for Soil Resources) with the following horizons: Ap-Bw-C (FAO, 2014; Marcinek, 2011). The physical soil parameters were determined using the sieve-hydrometer method according to PN-R-04032:1998. On this basis, the soil texture was classified as sandy loam with pH in H₂O of 4.90–5.96 (potentiometric method according to PN-ISO 10390:1997) and a C:N ratio of 6.57–8.33 in the upper 20 cm (Table 1). The granulometric composition and chemical properties and measurement methods of the soil are detailed in Table 1. Before planting, the soil was prepared by ploughing.

2.2 | Plant material

The plant material consisted of approximately 100 cm tall bare-root cuttings from 10 poplar cultivars. Two cultivars, *Populus maximowiczii* × *P. trichocarpa* (M × T; 'NE42' syn. 'Hybrid 275', or 'OP42') and *P. trichocarpa* (T) 'Fritzi Pauley', had previously been tested under Polish conditions in long rotation cycles and their usefulness for timber production was confirmed (Zajęczkowski, 2013; Zajęczkowski & Wojda, 2012). Four *P. × canadensis* cultivars (D × N; 'Degrosso', 'Albelo', 'Polargo' and 'Koster') produced by Luis Poloni (France) were recently released and have shown broad adaptability in tests throughout Europe (Stanton et al., 2014). Four Alasia Franco Vivai (AFV; Italy) cultivars (*P. deltoids* × *P. nigra* (D × N) 'AF2', *P. × generosa* × *P. trichocarpa* ((D × T) × T) 'AF8', *P. × generosa* × *P. nigra* (D × T) × N 'AF6' and 'Monviso') are new commercially available cultivars that are suitable for short rotation coppice, and have been increasingly used in commercial energy

FIGURE 1 Climatic diagram for the experimental site. The experimental site of the study was located in northern Poland (54°4'26"N, 20°30'4"E), near Lidzbark Warmiński. The monthly temperatures and sum of precipitation cover the period of 2015–2019, when the detailed measurements were done at the experimental area. The vertical bars denote minimum and maximum monthly averages for temperature (red; left panel) and a sum of precipitation (blue; right panel)

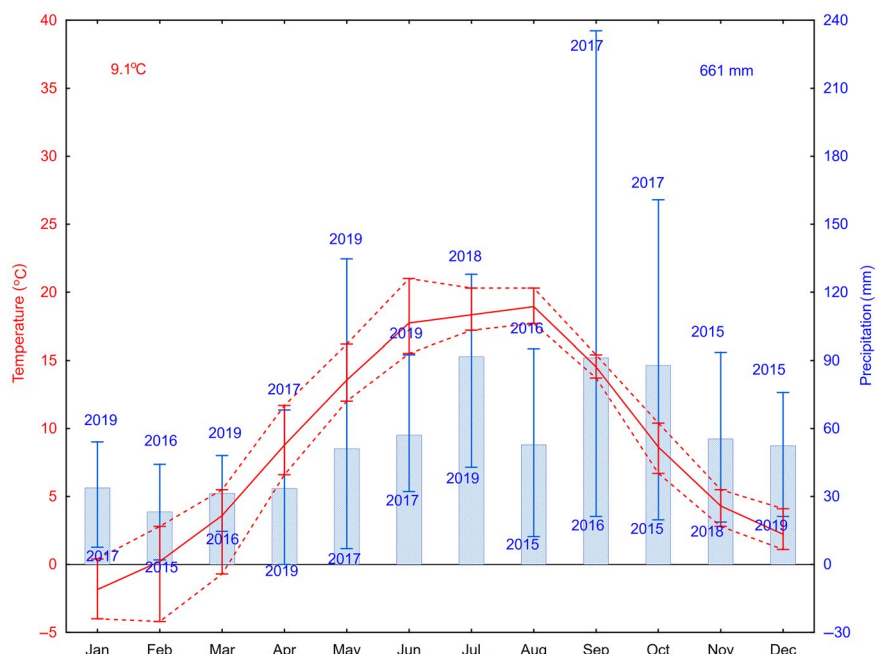


TABLE 1 Chemical characteristics and granulometric composition of the soil on the experimental area. The experimental site of the study was located in northern Poland (54°4'26"N, 20°30'4"E), near Lidzbark Warmiński. The measurement methods below

Particle size (mm) distribution (%) ^a				Chemical composition							
Values range				Values range							
Depth (cm)	2.00–0.05	0.05–0.002	<0.002	Ca (cmol kg ⁻¹) ^b	Mg (cmol kg ⁻¹) ^b	Na (cmol kg ⁻¹) ^b	K ₂ O (mg 100 g ⁻¹) ^c	P ₂ O ₅ (mg 100 g ⁻¹) ^d	C (%) ^e	N _{KJ} (%) ^f	C/N
0–20	69–75	20–25	5–8	1.3183–3.4863	0.2009–0.543	0.0151–0.0229	3.1214–9.3996	1.16–5.38	0.46–1.00	0.07–0.12	6.57–8.33
21–40	67–72	18–22	6–15	1.9537–4.8913	0.2665–1.0329	0.0153–0.0338	2.6211–8.8431	1.54–6.14	0.18–0.64	0.03–0.08	3.17–8.00

^aParticle size distribution for fractions <2 mm; separation of sand, silt and clay fractions: sieve-hydrometer method according to PN-R-04032:1998.

^bExchangeable cations Ca, Mg, Na: FAAS method in ammonium acetate extracts according to laboratory analytical procedure PB-03.

^cAssimilated potassium content (expressed as K₂O): FAAS method in Egner–Riehm extracts according to PN-R-04022: 1996.

^dAssimilated phosphorous content (expressed as P₂O₅): spectrophotometric method in Egner–Riehm extracts according to PN-R-04023: 1996.

^eTotal carbon content: dry combustion method with infrared detection according to PN-ISO 10694:2002.

^fKjeldahl nitrogen: distillation and titration method according to PN-ISO 11261:2002.

plantations in Poland in recent years. Due to the high mortality rate of 'Monviso' and 'AF6' cultivars at an early stage of the experiment, they were excluded from further analyses (Niemczyk et al., 2018).

2.3 | Study design

The study layout was comprised of a randomised complete block design with three replicates. Each block was divided into 10 plots equal to the number of the tested cultivars. Monocultivar individual plots were 10 rows wide by 10 columns deep. A total of 100, 1-year-old poplar rooted cuttings of a given cultivar were planted in April 2010 in holes within each plot with a spacing of 2.5 × 3.0 m, resulting in a planting density of 1333 ha⁻¹. A border row of excess trees of the tested cultivars was planted around the experimental area. The area was fenced to prevent browsing by wild animals. During the first two years, the plantation was weeded mechanically, once per annum. In this study, irrigation and fertilization were not applied.

2.4 | Measurement of tree characteristics

The survival rate and diameter at breast height (DBH; measured at a height of 1.3 m) of all trees were measured at the end of each growing season from 5 to 10 years. Whenever high mortality of trees of a particular cultivar was observed, the pathogenic species were isolated and identified using a taxonomic key (Barnett & Hunter, 1972; Crous et al., 2009; Cummins & Hiratsuka, 2003; Marcinkowska, 2012) on the basis of morphological characteristics that were determined with a stereoscope (Zeiss; Stemi 2000).

While dormant (winter period), 20% of the total initial number of trees (from each cultivar) were harvested each February from 2015 (5-year-old trees) to 2018 (8-year-old trees). Trees were harvested from two consecutive rows in each plot starting from the outside row and moving inward (20 trees per plot). In 2019, harvesting was undertaken twice on 10% of the remaining trees (one row each), once at the beginning of the season in February after nine years of growth and again in December after the 10th growing season. Height of trees was recorded for all harvested trees in each plot. On the basis of the DBH and height measurements, the height curve was constructed separately for each cultivar and year, according to the following function (Näslund, 1936):

$$h = \left(\frac{\text{DBH}}{\alpha + \beta * \text{DBH}} \right)^2 + 1.3, \quad (1)$$

where h represents tree height (m), DBH is the diameter at breast height (cm), α , β are the fitted coefficients, and 1.3

added to avoid the prediction of a zero height when the DBH approached zero.

The estimated coefficients (α , β) of the regression function for each cultivar was used to estimate the height of trees from the entire range of DBH, which was utilized in the volume equation (Equation 2). Tree volume was calculated based on the relationship between DBH, height and a form factor (Bruchwald, 1995), as:

$$V = \frac{\pi}{40,000} \text{DBH}^2 * h * f_{1.3}, \quad (2)$$

where V is the individual tree stem volume (m^3), h is tree height (m), DBH is the diameter at breast height (cm) and $f_{1.3}$ is form factor. The form factor was derived by Niemczyk and Bruchwald (2017) from the following empirical equation:

$$f_{1.3} = 0.5608 - 0.0127 * \text{DBH} + 0.0360 * \frac{h}{\text{DBH}}. \quad (3)$$

The fresh-weight biomass of each tree was recorded (to the nearest 1 g) in the field, immediately after a tree was harvested. Samples of trees representing each cultivar in a given block were taken to evaluate the moisture mass fraction. Samples were taken at the middle of every 2 m section, beginning from the stem base to the tree top. The total fresh dendromass of the samples represented approximately 10% of the total weight of each tree. All samples were numbered and transferred in paper bags to the laboratory immediately after collecting and weighing in the field. In the laboratory, samples were dried at 105°C until their weights stabilized. The moisture mass fraction was determined based on the difference in sample weight before (fresh biomass) and after drying (dry mass, DM), for each tree separately. Total DM yields for cultivars per unit area were determined from the weight of harvested fresh biomass obtained from a given replicate, reduced by the appropriate value of the moisture mass fraction and calculated for a given unit area per year, taking plant survival rate into account.

2.5 | Shoot characteristics and biomass production in the second 5-year rotation

To compare the productivity and other characteristics of cultivars between the two consecutive 5-year rotation cycles, the stumps from trees that were initially harvested after 5 years of growth were used. A number of shoots, height and diameter of shoots were measured after the second and fifth year (before harvest) of the second (coppice) rotation. All shoots which reached at least 50 cm in height were counted. The height of shoots was measured using the thickest shoot of each stump. The diameter of all shoots was measured at 50 cm height above ground level. The basal area (BA) was

calculated for all shoots per stump. Detailed measurements were carried out on alternating stumps in a row (10 stumps in each plot). In December 2019, that is, after 5 years in the second rotation, all trees were harvested and weighed in accordance with the procedure described in Section 2.4 above, to assess biomass production.

2.6 | Statistical analysis

To assess differences in productivity (volume, biomass and mean annual increment [MAI]) between cultivars and the interaction between cultivars over time during 10-year period, generalised linear mixed models were used. The model was expressed using the following equation:

$$y_{ijk} = \mu + C_i + T_j + (CT)_{ij} + b_k + e_{ijkl}, \quad (4)$$

where μ represents the general mean, C_i is the i -cultivar effect, T_j is the j -year effect, $(CT)_{ij}$ represents the ij -interaction between cultivar and time and b_k is the k -random block effect. Type III sum of squares (orthogonal) was used to determine the significance of these effects. The coefficient of variation (R^2) was used as a measure of the goodness of fit of the model, while the partial eta squared was used to describe the effect sizes. Partial eta squared (η_p^2) was expressed in per cent as the sum of squares of the effect (SS_{effect}) in relation to the sum of squares of the effect and the sum of squares of the error associated with the effect (SS_{error}), according to the equation (Lakens, 2013):

$$\eta_p^2 = \frac{SS_{\text{effect}}}{SS_{\text{effect}} + SS_{\text{error}}} * 100\%. \quad (5)$$

Post hoc comparisons between cultivars were performed using Tukey's honest significant difference test.

Data obtained for sprout characteristics of poplar cultivars measured after two and five growing seasons in the second 5-year rotation were tested using ANOVA and post hoc Tukey's test.

Data for biomass production obtained from two 5-year rotation cycles were similarly tested to 10-year rotation with generalized linear mixed models. A contrast analysis was used to compare biomass production of a given cultivar between the first and second 5-year rotation. The hypotheses $H_0: \mu_1 - \mu_2 = 0$ versus $H_1: \mu_1 - \mu_2 \neq 0$; where μ_1 represents the mean for a given cultivar in the first 5-year rotation and μ_2 represents the mean for the same cultivar in the second 5-year rotation, were verified by the significance of the contrast vector (L). The required vector with contrast weights was obtained directly from these hypotheses: $L = [-1 \ 1]$. The statistical significance of L was verified by the F -test and the calculated probability (p -value) of a value of an F . The degrees of freedom of the denominator of the F -test equal one (Haans, 2018). The null hypothesis was rejected if this probability was less

than or equal to the significance level $\alpha = 0.05$. All statistical analyses were performed with Statistica 10.0 statistical package ('StatSoft, Inc. and STATISTICA (Data Analysis Software System), Version 10, (2011)', n.d.).

3 | RESULTS

3.1 | Productivity of cultivars in a 10-year rotation cycle

All productivity characteristics differed significantly between cultivars, years and cultivar-by-year interactions were observed (Table 2). The stem volumes of individual trees increased between years in the 10-year rotation cycle. At the age of 5 years, individual tree stem volume ranged from 0.01 ('AF8') to 0.05 m³ ('NE42'), and from 0.05 m³ ('AF8') to 0.20 m³ ('NE42') after 10 years. Overall, the highest mean stem volumes of individual trees in the experiment were recorded for the cultivars traditionally used for timber production, 'Fritzi Pauley' followed by 'NE42'. In contrast, the new, short rotation coppice cultivar, 'AF8', had a significantly lower stem volume than all other cultivars (Figure 2a).

The ranks of cultivars, especially among the new cultivars, changed when calculating the stem volume on an area basis (taking survival rate into account). The highest volumes were achieved by the 'Fritzi Pauley' and 'NE42' in all measurement years, which were similar to the individual tree stem volume results. Both cultivars showed a large increment in growth after 8 years of production, achieving 257.5 and 236.0 m³ ha⁻¹ at age 10 respectively. At the same time, the volume per unit area for the four short rotation coppice cultivars decreased, which was associated with a high mortality rate. The most severe losses were observed in the two AFV cultivars ('AF2' and 'AF8'). These cultivars suffered heavily from infections caused by *Valsa sordida* (Nitschke), which resulted in a decrease in their survival rate and overall productivity to 34.9 and 22.7 m³ ha⁻¹ respectively, at the end of the 10-year rotation (Figure 2b). The mean annual increment for volume (MAI_V) mirrored the results for volume per unit area (Figure 2c). The MAI_V of four cultivars showed increasing values that progressed over time, while the MAI_V of the two AFV cultivars decreased at the end of the study period. In general, MAI_V reached its maximum and showed the largest variability at the end of the 10-year rotation cycle. At age 10, the MAI_V of the best performing cultivar amounted to 25.75 m³ ha⁻¹ year⁻¹ ('Fritzi Pauley'), while for the worst cultivar was only 2.27 m³ ha⁻¹ year⁻¹ ('AF8'), showing an 11-fold difference between these two cultivars.

'NE42' outperformed all other cultivars in biomass production calculated on a dry matter basis (Figure 2d–f). These differences in productivity were particularly evident after 8 years of growth, when mean annual increment of dry matter yield (MAI_{DM}) for that cultivar increased from 9.33 to

TABLE 2 Results of the linear mixed models for volume-based and biomass-based characteristics over time in the 10-year rotation of poplar cultivars

Effect	df	V (m ³)		V (m ³ ha ⁻¹)		MAI _V (m ³ ha ⁻¹ year ⁻¹)		DM _{I_{ind}} (kg)		DM (Mg ha ⁻¹)		MAI _{DM} (Mg ha ⁻¹ year ⁻¹)	
		$R^2 = 0.717$	η_p^2 (%)	F (p -value)	η_p^2 (%)	F (p -value)	$R^2 = 0.545$	$R^2 = 0.706$	F (p -value)	η_p^2 (%)	$R^2 = 0.722$	F (p -value)	$R^2 = 0.605$
Cultivar	7	471.639 (<0.001)	40.3	518.558 (<0.001)	41.3	341.588 (<0.001)	32.8	256.779 (<0.001)	45.8	346.834 (<0.001)	55.3	307.558 (<0.001)	50.3
Age	5	1162.46 (<0.001)	54.3	942.756 (<0.001)	48.2	178.689 (<0.001)	15.4	442.761 (<0.001)	51.0	360.568 (<0.001)	45.9	87.08 (<0.001)	17.0
Cultivar × Age	35	28.074 (<0.001)	16.7	33.624 (<0.001)	18.8	11.249 (<0.001)	7.4	15.668 (<0.001)	20.5	22.93 (<0.001)	27.4	11.407 (<0.001)	15.8
Block	2	251.385 (<0.001)	9.3	257.642 (<0.001)	9.2	283.866 (<0.001)	10.4	43.708 (<0.001)	3.9	43.362 (<0.001)	3.9	52.251 (<0.001)	4.7

Abbreviations: η_p^2 partial eta squared—note that partial eta squared does not sum up to 100%; DM, dry matter yield per unit area calculated taking tree survival rate into account; DM_{ind}, dry matter yield of individual tree; MAI_{DM}, mean annual increment of biomass dry matter yield; MAI_V, mean annual increment of volume on an area basis; R^2 , coefficient of determination; V , stem volume per unit area, calculated by taking tree survival rate into account; V_{ind}, stem volume of individual tree.

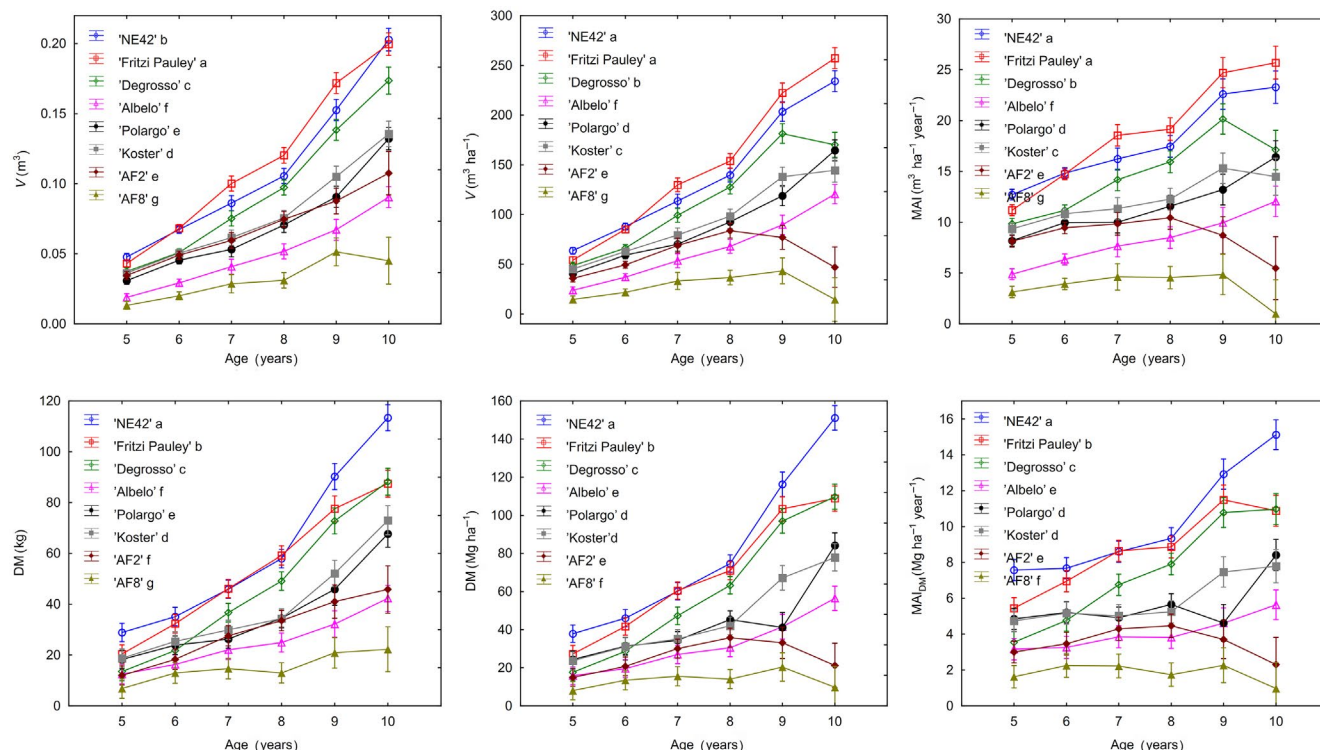


FIGURE 2 Trend lines of mean values \pm standard error (vertical bar) for: (a) stem volume of individual tree (V [m^3]), (b) volume on an area basis (V [$\text{m}^3 \text{ha}^{-1}$]), (c) mean annual increment of volume (MAI_V [$\text{m}^3 \text{ha}^{-1} \text{year}^{-1}$]), (d) dry matter yield of individual tree (DM [kg]), (e) dry matter yield per unit area (DM [$\text{Mg ha}^{-1} \text{year}^{-1}$]), (f) mean annual increment of dry matter yield (MAI_{DM} [$\text{Mg ha}^{-1} \text{year}^{-1}$]) for cultivars over time. The values expressed per unit area were calculated taking survival rate into account. The same lowercase letters next to the names of cultivars indicate statistically homogenous groups for cultivar effect at $p < 0.05$ in Tukey's HSD test. The detailed data for DBH, h , BA, form factor and volumes and DM yield with the Tukey's post hoc test results for the cultivar \times age effect were presented in Table S1. BA, basal area; DBH, diameter at breast height; HSD, honest significant difference

15.11 $\text{Mg ha}^{-1} \text{year}^{-1}$ at age 10 years. 'Degrosso' and 'Fritzi Pauley' achieved 11.00 and 10.98 $\text{Mg ha}^{-1} \text{year}^{-1}$, respectively, in the 10-year rotation cycle. In contrast, the biomass production of the worst-performing cultivar ('AF8') was only 1.00 $\text{Mg ha}^{-1} \text{year}^{-1}$ (Figure 2f). The detailed data for volume-based and biomass-based traits as well as additional metrics for DBH, h and BA over time in the 10-year rotation of poplar cultivars with Tukey's post hoc test results for the cultivar \times age effect are presented in Table S1.

Generally, biomass production was a good predictor of stem volume of individual trees, which was reflected in the high correlation between these two traits (0.984; $p < 0.001$; Figure 3a). However, these two characteristics should not be treated interchangeably without caution when a particular cultivar is considered. As the linear regression model showed, the largest residuals (plus and minus) were estimated repeatedly for the two best-performing cultivars. The estimated residuals for the 'NE42' cultivar always had negative values, while residuals for 'Fritzi Pauley' showed the opposite trend (Figure 3b). The analysis of variance and the post hoc Tukey test for residuals showed statistically significant differences between these two cultivars (Figure 3b). These results show that the larger stem volume estimated

for 'Fritzi Pauley' versus 'NE42' arises from considerable differences in biomass accumulation from the tree's crown and stems. The 'Fritzi Pauley' cultivar accumulates most of its biomass in the stem, while 'NE42' also accumulates biomass in the tree crown, which translates into a higher biomass, with a stem volume slightly lower than 'Fritzi Pauley'.

3.2 | Productivity and shoot characteristics of cultivars in the second 5-year rotation

Almost all cultivars resprouted vigorously in the second 5-year rotation. Detailed information regarding the first year after coppicing was described elsewhere (Niemczyk et al., 2016). After 2 years in the second rotation, the survival of shoots varied among cultivars but in general decreased considerably by the end of the second 5-year rotation, when the survival rate of stumps of most cultivars ranged from 0% ('AF8') to 50% ('Fritzi Pauley') (Table 3). The 'Degrosso' cultivar was the only one that maintained a high survival rate to the end of the second 5-year rotation cycle (96.7%). 'Degrosso' also distinguished itself from the other cultivars

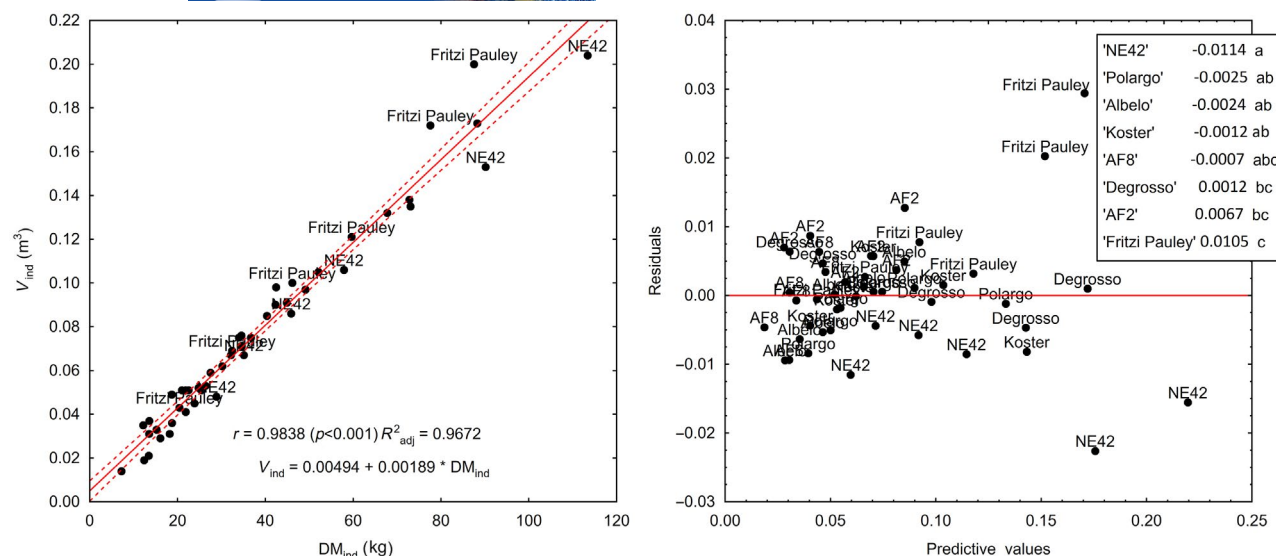


FIGURE 3 Linear regression (a) and correlation coefficient for stem volume of individual tree and dry matter of individual tree (DM_{ind}) as a predictor variable, (b) residuals for stem volume predictive values. In a frame: mean residuals and the results of post hoc Tukey's test. The same lowercase letters next to the names of cultivars and residual values indicate statistically homogenous groups at $p < 0.05$ in Tukey's HSD test, honest significant difference

by producing significantly taller sprouts in the second rotation cycle than in the first rotation (Table 3).

The number of 2-year-old shoots varied significantly between cultivars from 2.0 ('AF8') to 20.5 for 'Koster'. The number of shoots decreased significantly after 5 years of growth, from 1.5 ('AF2') to 5.1 ('Fritzi Pauley'). With time, thicker sprouts began to play an increasingly important role, at the expense of dying thinner shoots. This result was reflected in the growing BA proportion of the thickest shoot to an overall BA per stem (Table 3).

In terms of biomass production, the two 5-year rotation cycles differed significantly (Table 4). The trees harvested after 5 years of growth in the first rotation cycle produced significantly more biomass than stump sprouts in the second rotation cycle (Figure 4).

The contrast analysis showed significant differences in biomass production for individual cultivars between the first and second rotation cycle (Table S2). Generally, almost all cultivars produced considerably less DM, taking survival rate into account, in the second rotation cycle. The only exception from the weak biomass production and survival rate was the 'Degrosso' cultivar, which in the second 5-year rotation cycle produced significantly more biomass than in the first rotation cycle (Figure 4; Table S2).

3.3 | The total biomass production during two consecutive 5-year rotation cycles versus one 10-year rotation

Biomass production in longer, 10-year rotation was significantly greater than total biomass production in the two shorter

5-year rotation cycles. Overall, the mean total biomass production calculated on an area basis after 10 years—in two 5-year rotation cycles—was 25.3 Mg ha^{-1} , while the DM yield in a single 10-year rotation period was three times higher and amounted to 77.5 Mg ha^{-1} . The large values of η_p^2 ($>60\%$) calculated for both rotation length and cultivar showed the large effect size of the two variables (Figure 5).

Contrast analysis showed that six out of eight tested cultivars produced significantly more biomass in a single longer rotation than in two shorter rotation cycles (Figure 5; Table S3). The only exceptions were two AFV cultivars, 'AF2' and 'AF8', which showed no statistically significant differences in productivity in relation to rotation length. Cultivars 'AF2' and 'AF8' achieved the lowest productivity among the tested cultivars at the study site irrespective of the rotation length.

4 | DISCUSSION

The biomass production in this study covered rotation lengths of 5 and 10 years, which are rarely described in the literature. As the study showed, the productivity of poplars was affected by many factors including cultivar effect, rotation length, vulnerability to diseases, sprouting capacity and vitality and the interaction between cultivar and time. One of the primary factors affecting productivity was cultivar. The biomass productivity varied considerably among cultivars, ranging between 1.6 and $7.5 \text{ Mg ha}^{-1} \text{ year}^{-1}$ at the end of the 5-year rotation and 1 – $15 \text{ Mg ha}^{-1} \text{ year}^{-1}$ in the 10-year rotation period. Studies often report large variations ranging from less than 1 to over $25 \text{ Mg ha}^{-1} \text{ year}^{-1}$ among different cultivars under the same culture (Dillen

TABLE 3 The results of the ANOVA for sprout characteristics of poplar cultivars measured after two and five growing seasons in the second 5-year rotation. Average values \pm SE. The same letters indicate statistically homogenous groups (Tukey's test, $\alpha = 0.05$)

Cultivar	Cross type	H (m)	No of shoots per stem	BA (cm ²)	BA proportion of thickest shoot (%)	Survival (%)	H (m)	No of shoots per stem	BA (cm ²)	BA proportion of thickest shoot (%)	Survival (%)
<i>F</i> (<i>p</i> -value)		6.40 (<0.001)	3.35 (0.003)	3.33 (0.003)	1.12 (0.358)		29.30 (<0.001)	5.62 (<0.001)	20.78 (<0.001)	6.76 (<0.001)	
Characteristics		Two years after coppice					Five years after coppice				
'NE42'	M \times T	2.71 \pm 0.14 c	13.47 \pm 1.84 bc	2.69 \pm 0.39 b	22.48 \pm 5.02 ab	63.3	7.24 \pm 0.45 c	3.50 \pm 0.23 cb	65.06 \pm 8.57 cb	55.82 \pm 4.11 da	23.3
'Fritzi Pauley'	T	2.76 \pm 0.21 bc	9.84 \pm 1.11 c	2.29 \pm 0.32 b	26.21 \pm 6.18 ab	63.3	8.47 \pm 0.25 b	5.10 \pm 0.32 a	78.72 \pm 7.02 b	45.83 \pm 3.08 a	50
'Degrosso'	D \times N	3.83 \pm 0.14 a	14.07 \pm 1.20 b	3.53 \pm 0.24 a	22.22 \pm 3.10 ab	100.0	9.35 \pm 0.13 a	3.90 \pm 0.26 b	114.38 \pm 5.56 a	65.86 \pm 2.77 dc	96.7
'Albelo'	D \times N	3.25 \pm 0.13 b	12.38 \pm 1.79 bc	2.54 \pm 0.42 b	19.39 \pm 2.52 ab	43.3	6.94 \pm 0.26 c	2.38 \pm 0.22 d	31.67 \pm 2.89 d	77.43 \pm 3.84 b	35
'Polargo'	D \times N	2.56 \pm 0.16 bc	12.80 \pm 1.36 abc	2.00 \pm 0.25 b	14.91 \pm 1.96 b	16.7	4.63 \pm 0.49 d	2.67 \pm 0.60 dc	21.66 \pm 4.67 d	73.89 \pm 8.90 cb	15
'Koster'	D \times N	2.55 \pm 0.43 bc	20.50 \pm 2.99 a	2.85 \pm 0.69 ab	10.15 \pm 1.13 b	13.3	6.90 \pm 0.00 dc	4.00 \pm 0.00 dc	83.86 \pm 0.00 dc	43.30 \pm 0.00 dc	1.7
'AF2'	D \times N	2.92 \pm 0.18 bc	9.00 \pm 1.44 c	1.69 \pm 0.31 b	24.27 \pm 2.99 ab	26.7	5.00 \pm 0.40 d	1.5 \pm 0.5 dc	16.49 \pm 3.14 dc	80.12 \pm 19.88 dc	3.3
'AF8'	(D \times T) \times T	3.00 \pm 0.00 abc	2.00 \pm 0.00 c	0.61 \pm 0.00 b	56.41 \pm 0.00 a	3.3	0.00	0.00	0.00	0.00	0.0
Average		3.14 \pm 0.09	12.59 \pm 0.66	2.72 \pm 0.15	22.32 \pm 1.87		8.16 \pm 0.16	3.77 \pm 0.16	80.62 \pm 4.22	62.75 \pm 1.91	

Abbreviations: BA, basal area of all shoots per stump at 50 cm height above ground level; H, height of the thickest shoot

Cross type: M, *Populus maximowiczii*; D, *P. deltoides*; N, *P. nigra*; T, *P. trichocarpa*.

TABLE 4 Results of the linear mixed models for biomass-based characteristics of poplar cultivars in two 5-year rotation cycles

Effect	df	DM _{ind} (kg)		DM (Mg ha ⁻¹)		MAI _{DM} (Mg ha ⁻¹ year ⁻¹)	
		$R^2 = 0.452$		$R^2 = 0.548$		$R^2 = 0.548$	
		F (p-value)	η_p^2 (%)	F (p-value)	η_p^2 (%)	F (p-value)	η_p^2 (%)
Cultivar	7	32.59 (<0.001)	28.3	34.55 (<0.001)	29.5	34.55 (<0.001)	29.5
Rotation	1	23.33 (<0.001)	3.9	89.57 (<0.001)	13.4	89.57 (<0.001)	13.4
Cultivar × Rotation	6	15.96 (<0.001)	14.2	36.79 (<0.001)	27.6	36.79 (<0.001)	27.6
Block	2	19.71 (<0.001)	6.4	20.09 (<0.001)	6.5	20.09 (<0.001)	6.5

Abbreviations: η_p^2 , partial eta squared—note that partial eta squared does not sum up to 100%; DM, dry matter yield per unit area calculated taking tree's survival rate into account; DM_{ind}, dry matter yield of individual tree; MAI_{DM}, mean annual increment of biomass dry matter yield; R^2 , coefficient of determination.

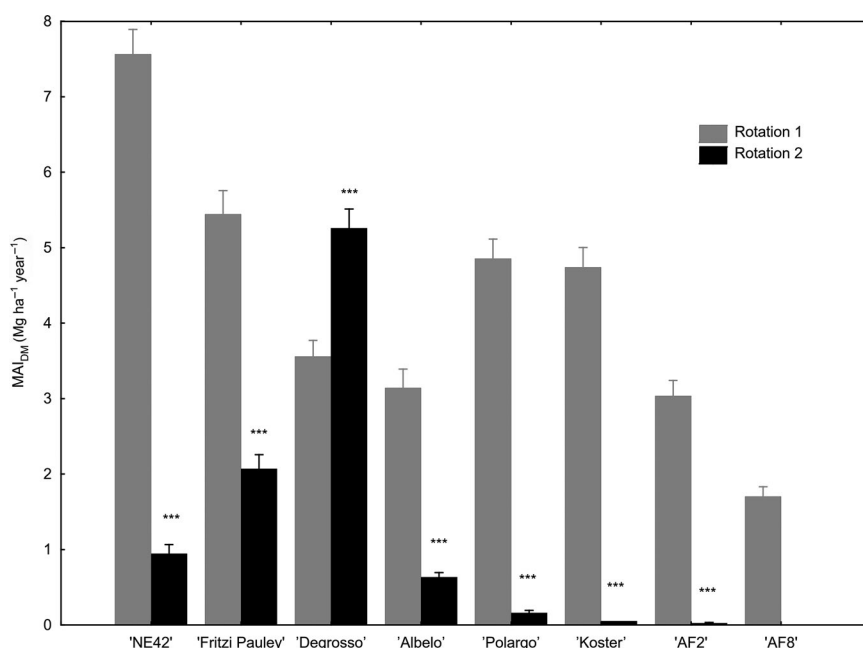


FIGURE 4 Mean annual increment for dry matter (DM) yield \pm standard error (vertical bars) of cultivars in two consecutive 5-year rotation cycles. The data for each cultivar were analysed using a contrast analysis. *** indicates a significant difference; $p < 0.05$.

et al., 2011; Vanbeveren & Ceulemans, 2018). However, the highest yields of 20–25 Mg ha⁻¹ year⁻¹ are expected to be achieved under suitable climatic conditions, such as in southern Europe (Manzone et al., 2009; Manzone & Calvo, 2016; Nassi O Di Nasso et al., 2010; Testa et al., 2014) and more southern locations in North America (Ghezehei et al., 2015, 2019, 2020), where fertilization and irrigation are applied. Yield capacity comparable to that achieved in the current study has been reported in other studies carried out in the northern regions of Europe. In northern Poland, the various clones achieved an MAI of 4.5–10 Mg ha⁻¹ year⁻¹ in two 4-year rotation cycles (Stolarski et al., 2020). In Belgium, the mean yield of the plantation was 12–16.5 Mg ha⁻¹ year⁻¹ (Vanbeveren & Ceulemans, 2018; Verlinden et al., 2015); in Denmark, it was 0.8–9.5 Mg ha⁻¹ year⁻¹ (Nielsen et al., 2014); and in Sweden, 3–10 Mg ha⁻¹ year⁻¹ (Christersson, 2010; Johansson, 2013; Karacic et al., 2003; Nordborg et al., 2018; Rytter & Stener, 2005).

The two cultivars, 'NE42' and 'Fritzi Pauley', traditionally used in timber production, expressed the best growth

performance during the current experiment. These two cultivars were also the top performers in other studies in temperate climatic conditions. In the Czech Republic, 'NE42' outperformed the native *P. nigra* clones (Benetka et al., 2014), while in Denmark, of 36 clones tested, 'NE42' and 'Fritzi Pauley' were the most productive, achieving 9.5 and 6.2 Mg ha⁻¹ year⁻¹, respectively, in 13 years of experiment (Nielsen et al., 2014). These results confirm good adaptability and plasticity in growth to diverse environmental conditions in these two cultivars. In contrast, cultivars 'AF2', 'AF6', 'AF8' and 'Monviso', tested in the current study, showed poor adaptation to the environmental conditions of the study site located in northern Poland. The tested AFV cultivars were characterized by the lowest biomass productivity (1–2 Mg ha⁻¹ year⁻¹) among all tested cultivars. The same cultivars ('AF2', 'AF6', 'AF8') achieved a productivity level of approximately 5 Mg ha⁻¹ year⁻¹ in northern Germany (51°N; Landgraf et al., 2020), while in southern Europe, the cultivars 'AF8' and 'Monviso' reached a mean biomass productivity level of 19 Mg ha⁻¹ year⁻¹ (Paris et al., 2011; Sabatti et al., 2014).

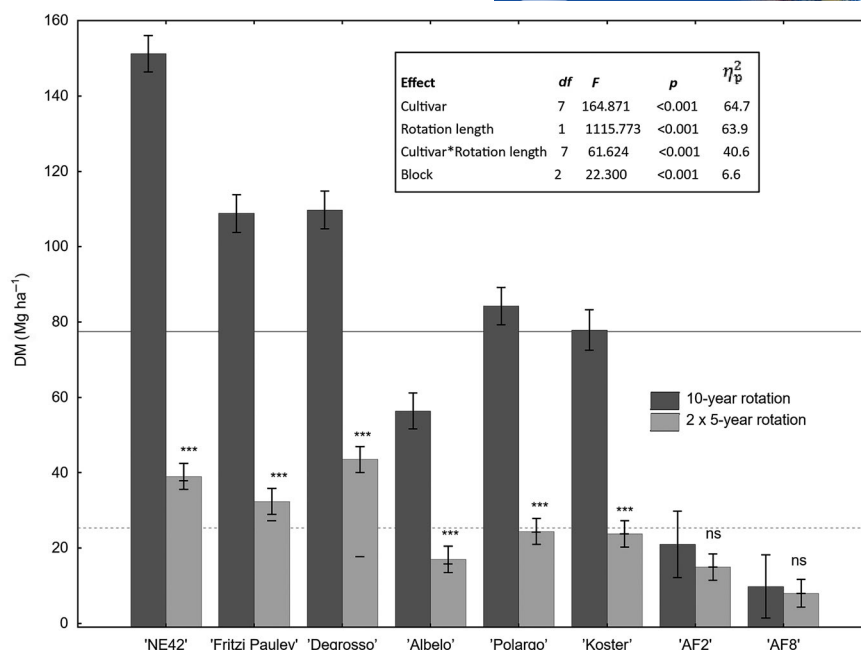


FIGURE 5 Total biomass production for dry matter (DM) yield on an area basis for cultivars in one 10-year rotation versus two consecutive 5-year rotation cycles: mean values \pm standard errors (vertical bars). In the frame results of linear mixed model ($R^2 = 0.839$) for total DM yield; η_p^2 expressed in %. The grey horizontal dotted line ($y = 25.3$) denotes mean DM yield (Mg ha^{-1}) for the two 5-year rotation cycles (overall 10 years of biomass production). The continue line ($y = 77.5$) represents mean DM yield (Mg ha^{-1}) for 10-year rotation length. The black segment in the middle of 2×5 -year rotation bars denotes DM produced in the first rotation. The data for each cultivar were analysed using a contrast analysis. *** indicates a significant difference between rotation length for given cultivar $p < 0.05$

Taking into account differences in biomass production among the different parental species and combinations of species, it was generally found that the *P. maximowiczii* \times *P. trichocarpa* hybrid and the intra-specific *P. trichocarpa* cross (s. *Tacamahaca*) performed better than *P. deltoides* or *P. nigra* crosses (s. *Aigeiros*). A similar difference between species and hybrid groups was observed in field trials in Sweden (Adler et al., 2021), Denmark (Nielsen et al., 2014) and Germany (Liu et al., 2017). The results of the poplar cultivar trials established from 1956 to 1982 in Poland (60 test sites, approximately 200 cultivars tested), also confirmed their differentiated hybrid- and species-dependent growth potential, as well as their resistance to diseases and frost (Zajęczkowski, 2013; Zajęczkowski & Wojda, 2012). The fast growing and most frost and disease-resistant cultivars were all hybrids of *P. maximowiczii*, while crosses of *P. nigra* were more susceptible to low temperatures and various diseases (Bugala, 1973). The large differences in performance between the different cultivars, especially within the *P. deltoides* and *P. nigra* crosses at the study site, may also arise from the geographical origin of the parent species. All parental species of tested cultivars occur in diverse environments and span wide geographical ranges. Genetic variation in adaptive traits for poplar species is generally associated with latitude in the form of clines (Stanton et al., 2010). Southern seed sources are often less tolerant of winter temperature extremes compared to more northern sources in common garden experiments

(Stanton et al., 2010). A range-wide study of growth, morphological and phenological characteristics of American *P. deltoides* provenances from 30° to 45°N latitude planted at 40°N latitude revealed this phenomenon, which followed a clinal pattern from N to S (Ying & Bagley, 1976). Therefore, cultivars bred from more southern provenances may be significantly less suitable for commercial use at northern latitudes ($\geq 54^\circ\text{N}$). The low productivity, susceptibility to *V. sordida* and high mortality rate of the AFV cultivars tested in the Lidzbark Warmiński trial (54°4'N), may therefore result directly from their maladaptation to the geographical and climatic conditions of northern Poland.

As the current study showed, the choice of rotation length had a strong influence on the productivity and sustainability of the plantation. The 5-year rotation, which in this study covered two harvests, produced highly diverse cultivar responses in terms of sprouting capacity, survivability and productivity in the subsequent cycle. Significant differences were observed in shoot regrowth from stumps of different cultivars. One year after coppice, the largest initial number of shoots per stem was produced by 'Koster', 'Fritzi Pauley' and 'NE42' cultivars (Niemczyk et al., 2016). In the second year of the second rotation, the 'Koster' cultivar maintained the largest number of shoots per stem, while the tallest shoots and overall BA were produced by the 'Degrosso' cultivar. The shoot number per stem decreased considerably at the end of the second rotation in all the researched cultivars. With time,

the thickest shoot started playing a dominant role, which is generally in agreement with other studies (Afes et al., 2008; Verlinden et al., 2015). Nonetheless, contrary to most studies (Benetka et al., 2014; Stolarski et al., 2020; Vanbeverem & Ceulemans, 2018; Verlinden et al., 2015), the productivity of individual cultivars in the second rotation was significantly lower than in the first rotation. The weak productivity was strongly associated with the high mortality rate of stumps, which in the case of 'AF8', 'AF2' and 'Koster' exceeded 90% by the end of the second rotation (10 years after establishment of the plantation). The only exception was the 'Degrosso' cultivar, which responded positively to coppicing, and was characterized by a high survival rate and a significantly higher biomass production in the second rotation in comparison to the first rotation (17.79 Mg ha⁻¹ in the first rotation vs. 25.85 Mg ha⁻¹ in the second rotation). Thus, the results obtained for the second 5-year rotation cycle suggest that the poplar's response to coppicing is highly cultivar-specific, and the performance of cultivars is complex, changing over time. Although cultivars resprouted vigorously, the survival rate at the end of the second rotation was low. It seems unlikely that adjacent rows of trees overshadowed the resprouting stumps since the nearest rows of trees were harvested in successive years. In the case of some cultivars, mortality at the end of the second rotation affected all stumps, which may rather suggest an unfavourable (i.e. too long) rotation length for coppicing. It seems possible that the large cross-sectional area of individual stumps in 5-year rotation increased the risk of stump wood being colonized by decay organisms that might, in turn, infect the sprouts. These conclusions seem to confirm the general observations of Dickmann and Stuart (1983) and Dickmann (2006), that stump sprouts are less desirable than trees established from suckers, cuttings or seedlings. The authors emphasize that stump sprouts tend to be short-lived, their form is often poor and decaying fungi may invade the sprouts from deteriorating stumps. Therefore, replanting after harvest seems to be an appropriate practice in longer rotation lengths (5-year and longer rotations). This finding shows potential risks for the sustainability, productivity and economic efficiency of plantations managed in 5-year rotation regime.

Due to the relatively low planting density in the current experiment, the production of biomass per unit area did not achieve satisfactory results at a younger age of trees; hence, the MAI for the best cultivar, 'NE42', at the age of 5 years was only 7.5 Mg ha⁻¹ year⁻¹, while at the age of 10 years, the same cultivar doubled its MAI, effectively utilizing the space for biomass production. In this aspect, the results confirm those of Armstrong et al., (1999) and Nassi O Di Nasso et al., (2010), who noticed that production rates increase when poplar plantations are grown with longer rotations. However, it is difficult to directly compare these results with the current study, as the studies only considered 1- to 3-year rotation lengths.

In the case of the shorter rotations considered in the current study, the only solution significantly influencing productivity improvement is the increase in the planting density, which would optimize the use of space by trees in the targeted rotation length. The choice of spacing is always a compromise (Jaworski, 2004). A wider spacing accelerates growth, limiting competition for resources between trees, but also contributes to insufficient soil protection, which, especially in the first years of plantation establishment, may have a negative effect on trees (weed competition). Higher densities result in faster canopy closure and relatively higher yields per unit area (Hauk et al., 2014). However, greater competition between trees and slightly weaker growth parameters, achieved by individuals, should be taken into account (Jaworski, 2004). Additional research is also needed to determine whether higher planting density and the potential profits resulting from the higher biomass yield would be able to compensate for the increase in cost associated with a higher number of seedlings and more frequent harvests, which are the most costly activities in the life cycle assessment of a plantation. In light of Buchholz and Volk's (2011) study, this is doubtful. Planting density should also be adjusted to a given cultivar. The two best-yielding cultivars in the current study, 'NE42' and 'Fritzi Pauley', differed significantly in terms of the shape of their crown and biomass allocation, which should not be ignored when choosing spacing and rotation length.

The choice of the rotation length can also be optimized by the stochastic model of the MAI over time (Assmann, 1968). The shape of the MAI curve shows the biological growth capacity of trees in specific conditions (Erteld & Eberhardt, 1966). At a young age, the volume increment in trees is insignificant. A clear rise in the growth curve occurs when the tree, according to the development of the crown and the root system, gains sufficient strength, and the BA and height are of appropriate sizes (Jaworski, 2004). Light-demanding tree species, such as poplars, show a rapid volume increment with an early culmination. In this experiment, a significant volume increment was expressed in most cultivars after 8 years of growth, while by 10 years of age, most cultivars had achieved their highest MAI in the experiment. The results suggest therefore that trees in more northern geographical locations can achieve better biomass production with extended rotation lengths and that an age ≥ 10 is the biologically optimal rotation age as the slope of MAI is equal/close to zero. Such rotations use the biological growth abilities of the trees in a more natural way. As emphasized by Hauk et al., (2014), advantages in increasing the rotation length are higher yields and better wood quality, due to an increase in the wood mass fraction relative to the bark mass fraction. Changes in tree sizes, however, will entail anticipating the choice of harvesting machinery and economic profitability of

the plantation. Each harvesting machine is not only constrained by weather and field conditions but also by several feedstock characteristics (Vanbeveren & Ceulemans, 2018). As Burger (2010) stated, an economically competitive and ecologically preferable alternative to fully mechanised harvesting techniques, is manual harvesting of 10-year-old poplars. This is contrary to 5-year-old stands, where manual harvesting is the most expensive harvesting technique, because of the smaller biomass per tree (Burger, 2010).

To conclude, this study showed that 10-year rotation produced significantly more sustainable biomass in comparison to two, consecutive 5-year rotation cycles. Other advantages of longer rotations arise from less impact on environment (Griffiths et al., 2019), a better GHG budget (creation of a GHG sink; Horemans et al., 2019) and positive influences on biodiversity (Griffiths et al., 2019), which together make them more similar to forest systems. Such rotations use the biological growth abilities of the trees more naturally. In the case of longer rotation lengths (≥ 5 -year rotations), replanting (not resprouting) after harvest seems to be an appropriate practice for regeneration.

The tested cultivars showed large variability in biomass production and survivability. The AFV cultivars tested in this study ('Monviso', 'AF2', 'AF6', 'AF8') showed maladaptation to the temperate continental climatic conditions, while the traditional timber cultivars, which have been planted in Poland for many years, showed their superiority in the SRWC system. Although this study was not specifically designed to evaluate the economic profitability of plantations, the results demonstrate that poplar plantations with a rotation of 10 years and using best-performing cultivars could prove profitable and a sustainable investment for farmers and other landowners/investors. The study also demonstrated the importance of testing cultivars before introducing them on a commercial scale in situ. Valuable information pertaining to the choice of poplar cultivars and rotation lengths for stakeholders in the biomass market in temperate continental climatic zone has been produced. Given the importance of searching for new sources of renewable energy, it would, however, be appropriate to examine SRWC from a financial point of view, and above all, develop a selection and breeding programme for poplars at the local and/or national scales, considering climatic zones in the selection of parental material, and using advanced breeding strategies involving interspecific and intraspecific hybridization.

ACKNOWLEDGEMENTS

I wish to express my gratitude to Prof. Barb R. Thomas (University of Alberta, Canada) for valuable comments to the manuscript and linguistic support, Prof. Jarosław Socha (University of Agriculture in Krakow, Poland) for fruitful conversation about data analyses and my colleagues

from the Forest Research Institute: Dr. Tomasz Wojda, Piotr Zajączkowski, Szymon Krajewski and Władysław Kantorowicz for their contributions to field data collection.

CONFLICT OF INTEREST

The author declares no conflict of interest. The funders had no role in the design of the study; in the collection, analyses or interpretation of data; in the writing of the manuscript; or in the decision to publish the results.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the author upon reasonable request.

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REFERENCES

- Adler, A., Karacic, A., Wästljung, A.-C.-R., Johansson, U., Liepins, K., Gradeckas, A., & Christersson, L. (2021). Variation of growth and phenology traits in poplars planted in clonal trials in Northern Europe – Implications for breeding. *BioEnergy Research*. <https://doi.org/10.1007/s12155-021-10262-8>
- Afas, N. A., Marron, N., Van Dongen, S., Laureysens, I., & Ceulemans, R. (2008). Dynamics of biomass production in a poplar coppice culture over three rotations (11 years). *Forest Ecology and Management*, 255(5–6), 1883–1891. <https://doi.org/10.1016/j.foreco.2007.12.010>
- Armstrong, A., Johns, C., & Tubby, I. (1999). Effects of spacing and cutting cycle on the yield of poplar grown as an energy crop. *Biomass and Bioenergy*, 17(4), 305–314. [https://doi.org/10.1016/S0961-9534\(99\)00054-9](https://doi.org/10.1016/S0961-9534(99)00054-9)
- Assmann, E. (1968). *Forest yield science*. (Ied., p. 628). Państwowe Wydawnictwo Rolnicze i Leśne.
- Barnett, H. L., & Hunter, B. B. (1972). Illustrated genera of imperfect fungi. v+241 pp.
- Benetka, V., Novotná, K., & Štochlová, P. (2014). Biomass production of *Populus nigra* L. clones grown in short rotation coppice systems in three different environments over four rotations. *IForest*, 7(4), 233–239. <https://doi.org/10.3832/ifor1162-007>
- Benomar, L., DesRochers, A., & Larocque, G. R. (2012). The effects of spacing on growth, morphology and biomass production and allocation in two hybrid poplar clones growing in the boreal region of Canada. *Trees – Structure and Function*, 26(3), 939–949. <https://doi.org/10.1007/s00468-011-0671-6>
- Bruchwald, A. (1995). *Dendrometria*. Wydawnictwo SGGW.
- Buchholz, T., & Volk, T. A. (2011). Improving the profitability of willow crops-identifying opportunities with a crop budget model. *Bioenergy Research*, 4(2), 85–95. <https://doi.org/10.1007/s12155-010-9103-5>
- Bugała, W. (1973). Systematyka i zmienność. In W. Bugała (Ed.), *Topole Populus L.* Państwowe Wydawnictwo Naukowe.
- Burger, F. J. (2010). *Bewirtschaftung und Ökobilanzierung von Kurzumtriebsplantagen* (Ph.D. Thesis). Technischen Universität München. 40 pp.
- Ceulemans, R., McDonald, A. J. S., & Pereira, J. S. (1996). A comparison among eucalypt, poplar and willow characteristics



- with particular reference to a coppice, growth-modelling approach. *Biomass and Bioenergy*, 11(2–3), 215–231. [https://doi.org/10.1016/0961-9534\(96\)00035-9](https://doi.org/10.1016/0961-9534(96)00035-9)
- Christersson, L. (2010). Wood production potential in poplar plantations in Sweden. *Biomass and Bioenergy*, 34(9), 1289–1299. <https://doi.org/10.1016/j.biombioe.2010.03.021>
- Clifton-Brown, J., Harfouche, A., Casler, M. D., Dylan Jones, H., Macalpine, W. J., Murphy-Bokern, D., Smart, L. B., Adler, A., Ashman, C., Awty-Carroll, D., Bastien, C., Bopper, S., Botnari, V., Brancourt-Hulmel, M., Chen, Z., Clark, L. V., Cosentino, S., Dalton, S., Davey, C., ... Lewandowski, I. (2019). Breeding progress and preparedness for mass-scale deployment of perennial lignocellulosic biomass crops switchgrass, miscanthus, willow and poplar. *GCB Bioenergy*, 11(1), 118–151. <https://doi.org/10.1111/gcbb.12566>
- Crous, P. W., Verkley, G. J. M., Groenewald, J. Z., & Samson, R. A. (2009). *Fungal biodiversity. CBS Laboratory manual series*. Westerdijk Fungal Biodiversity Institute.
- Cummins, G. B., & Hiratsuka, Y. (2003). *Illustrated genera of rust fungi*. American Phytopathological Society (APS Press).
- Dickmann, D. I. (2006). Silviculture and biology of short-rotation woody crops in temperate regions: Then and now. *Biomass and Bioenergy*, 30(8–9), 696–705. <https://doi.org/10.1016/j.biombioe.2005.02.008>
- Dickmann, D. I., & Stuart, K. W. (1983). *The Culture of poplars in eastern North America*. Michigan State University East Lansing USA. 168 pp.
- Dillen, S. Y., Djomo, S. N., Al Afas, N., Vanbeveren, S., & Ceulemans, R. (2013). Biomass yield and energy balance of a short-rotation poplar coppice with multiple clones on degraded land during 16 years. *Biomass and Bioenergy*, 56, 157–165. <https://doi.org/10.1016/j.biombioe.2013.04.019>
- Dillen, S., Vanbeveren, S., Al Afas, N., Laureysens, I., Croes, S., & Ceulemans, R. (2011). Biomass production in a 15-year-old poplar short-rotation coppice culture in Belgium. *Aspects of Applied Biology*, 112(November), 99–106.
- Erteld, W., & Eberhardt, H. (1966). *Waldtragslehre*. Neumann.
- EU. (2018). Directive (EU) 2018/2001 of the European Parliament and of the Council on the promotion of the use of energy from renewable sources. *Official Journal of the European Union*, 2018(L 328), 82–209. <https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32018L2001&from=EN>
- FAO. (2014). World reference base for soil resources 2014. International soil classification system for naming soils and creating legends for soil maps. World Soil Resources Reports No. 106. <https://doi.org/10.1017/S0014479706394902>
- Ghezehei, S. B., Nichols, E. G., Maier, C. A., & Hazel, D. W. (2019). Adaptability of populus to physiography and growing conditions in the southeastern USA. *Forests*, 10(2), 118. <https://doi.org/10.3390/f10020118>
- Ghezehei, S. B., Shifflett, S. D., Hazel, D. W., & Nichols, E. G. (2015). SRWC bioenergy productivity and economic feasibility on marginal lands. *Journal of Environmental Management*, 160, 57–66. <https://doi.org/10.1016/j.jenvman.2015.05.025>
- Ghezehei, S. B., Wright, J., Zalesny, R. S., Nichols, E. G., & Hazel, D. W. (2020). Matching site-suitable poplars to rotation length for optimized productivity. *Forest Ecology and Management*, 457(February), 117670. <https://doi.org/10.1016/j.foreco.2019.117670>
- Griffiths, N. A., Rau, B. M., Vaché, K. B., Starr, G., Bitew, M. M., Aubrey, D. P., Martin, J. A., Benton, E., & Jackson, C. R. (2019). Environmental effects of short-rotation woody crops for bioenergy: What is and isn't known. *GCB Bioenergy*, 11(4), 554–572. <https://doi.org/10.1111/gcbb.12536>
- Haans, A. (2018). Contrast analysis: A tutorial. *Practical Assessment, Research and Evaluation*, 23(9), 1–21. <https://doi.org/10.7275/zeyh-j468>
- Hauk, S., Knoke, T., & Wittkopf, S. (2014). Economic evaluation of short rotation coppice systems for energy from biomass – A review. *Renewable and Sustainable Energy Reviews*, 29, 435–448. <https://doi.org/10.1016/j.rser.2013.08.103>
- Horemans, J. A., Arriga, N., & Ceulemans, R. (2019). Greenhouse gas budget of a poplar bioenergy plantation in Belgium: CO₂ uptake outweighs CH₄ and N₂O emissions. *GCB Bioenergy*, 11(12), 1435–1443. <https://doi.org/10.1111/gcbb.12648>
- Jåstad, E. O., Bolkesjø, T. F., Trømborg, E., & Rørstad, P. K. (2020). The role of woody biomass for reduction of fossil GHG emissions in the future North European energy sector. *Applied Energy*, 274(June), 115360. <https://doi.org/10.1016/j.apenergy.2020.115360>
- Jaworski, A. (2004). *Podstawy przyrostowe i ekologiczne odnawiania oraz pielęgnacji drzewostanów*. Państwowe Wydawnictwo Rolnicze i Leśne.
- Johansson, T. (2013). Biomass production of hybrid aspen growing on former farm land in Sweden. *Journal of Forestry Research*, 24(2), 237–246. <https://doi.org/10.1007/s11676-012-0305-x>
- Karacic, A., Verwijst, T., & Weih, M. (2003). Above-ground woody biomass production of short-rotation *Populus* plantations on agricultural land in Sweden. *Scandinavian Journal of Forest Research*, 18(5), 427–437. <https://doi.org/10.1080/02827580310009113>
- Lakens, D. (2013). Calculating and reporting effect sizes to facilitate cumulative science: A practical primer for t-tests and ANOVAs. *Frontiers in Psychology*, 4(NOV), 1–12. <https://doi.org/10.3389/fpsyg.2013.00863>
- Landgraf, D., Carl, C., & Neupert, M. (2020). Biomass yield of 37 different SRC poplar varieties grown on a typical site in north eastern Germany. *Forests*, 11(10), 1–16. <https://doi.org/10.3390/f11101048>
- Liu, N., Larsen, S. U., Jørgensen, U., Murach, D., Pflugmacher, C., Hartmann, H., & Lærke, P. E. (2017). Combustion quality of poplar and willow clones grown as SRC at four sites in Brandenburg, Germany. *Biomass and Bioenergy*, 106, 51–62. <https://doi.org/10.1016/j.biombioe.2017.08.020>
- Manzone, M., Airoldi, G., & Balsari, P. (2009). Energetic and economic evaluation of a poplar cultivation for the biomass production in Italy. *Biomass and Bioenergy*, 33(9), 1258–1264. <https://doi.org/10.1016/j.biombioe.2009.05.024>
- Manzone, M., & Calvo, A. (2016). Energy and CO₂ analysis of poplar and maize crops for biomass production in north Italy. *Renewable Energy*, 86, 675–681. <https://doi.org/10.1016/j.renene.2015.08.047>
- Marcinek, J., Komisarek, J., Bednarek, R., Mocek, A., Skiba, S., & Wiatrowska, K. (2011). Systematyka gleb polski. In J. Marcinek & J. Komisarek (Eds.), *Polskie towarzystwo gleboznawcze*. Wydawnictwo “Wieś Jutra”. 195 pp.
- Marcinkowska, J. (2012). *Oznaczanie rodzajów grzybów sensu lato ważnych w fitopatologii*. Powszechne Wydawnictwo Rolnicze i Leśne.
- Näslund, M. (1936). Skogsförsöksanstaltens gallringsförsök i tallskog. *Meddelanden Från Statens Skogsförsöksanstalt*, 29, 1–169.
- Nassi O Di Nasso, N., Nasso, N., Guidi, W., Ragaglini, G., Tozzini, C., & Bonari, E. (2010). Biomass production and energy balance

- of a 12-year-old short-rotation coppice poplar stand under different cutting cycles. *GCB Bioenergy*, 2(2), 89–97. <https://doi.org/10.1111/j.1757-1707.2010.01043.x>
- Nielsen, U. B., Madsen, P., Hansen, J. K., Nord-Larsen, T., & Nielsen, A. T. (2014). Production potential of 36 poplar clones grown at medium length rotation in Denmark. *Biomass and Bioenergy*, 64, 99–109. <https://doi.org/10.1016/j.biombioe.2014.03.030>
- Niemczyk, M., & Bruchwald, A. (2017). Equations for diameter at the breast height form factor of poplar and its hybrids. *Sylvan*, 161(5), 413–421. <https://doi.org/10.26202/sylvan.2017020>
- Niemczyk, M., Kaliszewski, A., Jewiarz, M., Wróbel, M., & Mudryk, K. (2018). Productivity and biomass characteristics of selected poplar (*Populus* spp.) cultivars under the climatic conditions of northern Poland. *Biomass and Bioenergy*, 111, 46–51. <https://doi.org/10.1016/j.biombioe.2018.02.002>
- Niemczyk, M., Wojda, T., & Kaliszewski, A. (2016). Biomass productivity of selected poplar (*Populus* spp.) cultivars in short rotations in northern Poland. *New Zealand Journal of Forestry Science*, 46(1). <https://doi.org/10.1186/s40490-016-0077-8>
- Njakou Djomo, S., Ac, A., Zenone, T., De Groote, T., Bergante, S., Facciotto, G., Sixto, H., Ciria Ciria, P., Weger, J., & Ceulemans, R. (2015). Energy performances of intensive and extensive short rotation cropping systems for woody biomass production in the EU. *Renewable and Sustainable Energy Reviews*, 41, 845–854. <https://doi.org/10.1016/j.rser.2014.08.058>
- Nordborg, M., Berndes, G., Dimitriou, I., Henriksson, A., Mola-Yudego, B., & Rosenqvist, H. (2018). Energy analysis of poplar production for bioenergy in Sweden. *Biomass and Bioenergy*, 112(July 2017), 110–120. <https://doi.org/10.1016/j.biombioe.2018.01.021>
- Paris, P., Mareschi, L., Sabatti, M., Pisanelli, A., Ecosse, A., Nardin, F., & Scarascia-Mugnozza, G. (2011). Comparing hybrid *Populus* clones for SRF across northern Italy after two biennial rotations: Survival, growth and yield. *Biomass and Bioenergy*, 35(4), 1524–1532. <https://doi.org/10.1016/j.biombioe.2010.12.050>
- Qin, Z., Zhuang, Q., Cai, X., He, Y., Huang, Y., Jiang, D., Lin, E., Liu, Y., Tang, Y. A., & Wang, M. Q. (2018). Biomass and biofuels in China: Toward bioenergy resource potentials and their impacts on the environment. *Renewable and Sustainable Energy Reviews*, 82(June), 2387–2400. <https://doi.org/10.1016/j.rser.2017.08.073>
- Ragauskas, A. J., Williams, C. K., Davison, B. H., Britovsek, G., Cairney, J., Eckert, C. A., & Tschaplinski, T. (2006). The path forward for biofuels and biomaterials. *Science*, 311(5760), 484–489. <https://doi.org/10.1126/science.1114736>
- Rosso, L., Facciotto, G., Bergante, S., Vietto, L., & Nervo, G. (2013). Selection and testing of *Populus alba* and *Salix* spp. as bioenergy feedstock: Preliminary results. *Applied Energy*, 102, 87–92. <https://doi.org/10.1016/j.apenergy.2012.07.042>
- Rytter, L., & Stener, L. G. (2005). Productivity and thinning effects in hybrid aspen (*Populus tremula* L. × *P. tremuloides* Michx.) stands in southern Sweden. *Forestry*, 78(3), 285–295. <https://doi.org/10.1093/forestry/cpi026>
- Sabatti, M., Fabbrini, F., Harfouche, A., Beritognolo, I., Mareschi, L., Carlini, M., Paris, P., & Scarascia-Mugnozza, G. (2014). Evaluation of biomass production potential and heating value of hybrid poplar genotypes in a short-rotation culture in Italy. *Industrial Crops and Products*, 61(2014), 62–73. <https://doi.org/10.1016/j.indcrop.2014.06.043>
- Smith, P., Davies, C. A., Ogle, S., Zanchi, G., Bellarby, J., Bird, N., Boddey, R. M., McNamara, N. P., Powlson, D., Cowie, A., Noordwijk, M., Davis, S. C., Richter, D. D. E. B., Kryzanowski, L., Wijk, M. T., Stuart, J., Kirtton, A., Eggar, D., Newton-Cross, G., ... Braimoh, A. K. (2012). Towards an integrated global framework to assess the impacts of land use and management change on soil carbon: Current capability and future vision. *Global Change Biology*, 18(7), 2089–2101. <https://doi.org/10.1111/j.1365-2486.2012.02689.x>
- Stanton, B. J., Neale, D. B., & Li, S. (2010). Genetics and genomics of *Populus*. In *Populus breeding: From the classical to the genomic approach* (pp. 309–348). <https://doi.org/10.1007/978-1-4419-1541-2>
- Stanton, B. J., Serapiglia, M. J., & Smart, L. B. (2014). The domestication and conservation of *Populus* and *Salix* genetic resources. In U. K. Wallingford (Ed.), *Poplars and willows: Trees for society and the environment* (pp. 124–199). CAB International.
- Statistics Poland. (2020). Energy. Enterprises Department, Energy and Raw Materials Balances Section. 26 pp.
- StatSoft, Inc. (2011). STATISTICA version 10. <https://www.statsoft.pl/statistica-10/>
- Steenackers, J., Steenackers, M., Steenackers, V., & Stevens, M. (1996). Poplar diseases, consequences wood quality on growth. *Biomass and Bioenergy*, 10, 267–274. [https://doi.org/10.1016/0961-9534\(95\)00121-2](https://doi.org/10.1016/0961-9534(95)00121-2)
- Stettler, R. F., Bradshaw, H. D., Heilmann, P. E., & Hinckley, T. M. (1996). *Biology of populus and its implications for management and conservation*. National Research Council Canada. ISBN 0-660-16506-6.
- Stolarski, M. J., Warminiński, K., & Krzyżaniak, M. (2020). Energy value of yield and biomass quality of poplar grown in two consecutive 4-year harvest rotations in the north-east of Poland. *Energies*, 13(6), 1495. <https://doi.org/10.3390/en13061495>
- Testa, R., Di Trapani, A. M., Foderà, M., Sgroi, F., & Tudisca, S. (2014). Economic evaluation of introduction of poplar as biomass crop in Italy. *Renewable and Sustainable Energy Reviews*, 38(2014), 775–780. <https://doi.org/10.1016/j.rser.2014.07.054>
- Vanbeveren, S. P. P., & Ceulemans, R. (2018). Genotypic differences in biomass production during three rotations of short-rotation coppice. *Biomass and Bioenergy*, 119(May), 198–205. <https://doi.org/10.1016/j.biombioe.2018.09.027>
- Verlinden, M. S., Broeckx, L. S., & Ceulemans, R. (2015). First vs. second rotation of a poplar short rotation coppice: Above-ground biomass productivity and shoot dynamics. *Biomass and Bioenergy*, 73, 174–185. <https://doi.org/10.1016/j.biombioe.2014.12.012>
- Volk, T. A., Berguson, B., Daly, C., Halbleib, M. D., Miller, R., Rials, T. G., Abrahamson, L. P., Buchman, D., Buford, M., Cunningham, M. W., Eisenbies, M., Fabio, E. S., Hallen, K., Heavey, J., Johnson, G. A., Kuzovkina, Y. A., Liu, B. O., McMahon, B., Rousseau, R., ... Wright, J. (2018). Poplar and shrub willow energy crops in the United States: Field trial results from the multiyear regional feedstock partnership and yield potential maps based on the PRISM-ELM model. *GCB Bioenergy*, 10(10), 735–751. <https://doi.org/10.1111/gcbb.12498>
- Yan, Y. (2018). Integrate carbon dynamic models in analyzing carbon sequestration impact of forest biomass harvest. *Science of the Total Environment*, 615, 581–587. <https://doi.org/10.1016/j.scitotenv.2017.09.326>
- Yáñez, M. A., Zamudio, F., Espinoza, S., Guerra, F., Espinosa, C., & Baettig, R. M. (2019). Genetic variation and growth stability of hybrid poplars in high-density short-rotation coppice stands in central Chile. *Biomass and Bioenergy*, 120, 84–90. <https://doi.org/10.1016/j.biombioe.2018.11.011>

- Ying, C.-C., & Bagley, W. T. (1976). Genetic variation of eastern cottonwood in an eastern Nebraska provenance study. *Silvae Genetica*, 25(2), 67–73.
- Zajączkowski, K. (2013). *Hodowla lasu: Plantacje drzew szybko rosnących*. Powszechne Wydawnictwo Rolnicze i Leśne.
- Zajączkowski, K., & Wojda, T. (2012). Plantacje topolowe w przyrodniczych warunkach Polski. *Studia I Materiały Centrum Edukacji Przyrodniczo-Leśnej*, 33, 136–142.
- Zalesny, R. S. J., & Headlee, W. L. (2015). Developing woody crops for the enhancement of ecosystem services under changing climates in the north central United States. *Journal of Forest and Environmental Science*, 31(2), 78–90. <https://doi.org/10.7747/jfes.2015.31.2.78>
- Zappa, W., Junginger, M., & van den Broek, M. (2019). Is a 100% renewable European power system feasible by 2050? *Applied Energy*, 233–234, 1027–1050. <https://doi.org/10.1016/j.apenergy.2018.08.109>
- Zeman, F. S., & Keith, D. W. (2008). Carbon neutral hydrocarbons. *Philosophical Transactions of the Royal Society A: Mathematical,*

Physical and Engineering Sciences, 366(1882), 3901–3918. <https://doi.org/10.1098/rsta.2008.0143>

- Zhang, J., Song, X., Zhang, L., Jia, H., Peng, X., Zhao, Z., & Hu, J. (2020). Agronomic performance of 27 *Populus* clones evaluated after two 3-year coppice rotations in Henan, China. *GCB Bioenergy*, 12(2), 168–181. <https://doi.org/10.1111/gcbb.12662>

SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section.

How to cite this article: Niemczyk M. The effects of cultivar and rotation length (5 vs. 10 years) on biomass production and sustainability of poplar (*Populus* spp.) bioenergy plantation. *GCB Bioenergy*. 2021;13:999–1014. <https://doi.org/10.1111/gcbb.12827>