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Biomass productivity of selected poplar (*Populus* spp.) cultivars in short rotations in northern Poland§

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Abstract

Background: Renewable energy sources such as biomass are an important aspect of the energy policy of the European Union. As the use of 'full-value wood' for energy purposes has been restricted, short-rotation forestry may be an alternative source of woody biomass. In Poland, the most promising genus is poplar (*Populus* spp.).

Methods: Ten poplar cultivars from the *Aigeiros* or *Tacamahaca* sections of the genus *Populus* were compared in 5- and 6-year rotations for biomass components and yields. Additional aims were to preliminarily (a) identify a suitable rotation length and (b) evaluate the sprouting capacity of various cultivars in the climate of northern Poland. The following variables were measured: diameter at breast height (DBH), height, survival rate, single-tree dry mass, crop biomass production, and sprouting ability.

Results: The cultivars 'NE-42' and 'Fritzi Pauley' showed the best growth characteristics (DBH and height) and highest biomass production (7.6 and 7.7 t ha^{-1} $year^{-1}$, and 5.2 and 6.9 t ha^{-1} $year^{-1}$, respectively, for cultivars in the 5- and 6-year cycles). These cultivars were also distinguished by a large number of coppice shoots and a high shoot length. Eight cultivars did well enough to produce worthwhile data, and five of these gave higher biomass production (t DM ha^{-1} $year^{-1}$) during the 6-year, as opposed to the 5-year cycle. Of the eight cultivars analysed, 'AF-8' had the poorest growth parameters and produced two thirds less dry biomass than either the 'NE-42' or 'Fritzi Pauley' cultivars. Data for two Italian cultivars ('AF-6' and 'MON') were not analysed because of their cold tenderness and their high mortality.

Conclusions: Rotation length is important for biomass production in energy plantations. Most of the tested poplar cultivars gave higher biomass productivity over an initial 6-year cycle than over a 5-year one. Our preliminary results suggest that the 'NE-42' and 'Fritzi Pauley' cultivars performed best among those tested. Both of these have been tested previously in Poland in medium and long rotations. The data indicate the importance of testing cultivars under local climatic conditions before planting on a commercial scale.

Keywords: 'NE-42', 'Fritzi Pauley', Short-rotation coppice, Biomass productivity, *Populus* cultivar

Background

Expanding the use of renewable energy sources, such as woody biomass, is important in the European Union (EU). Such energy resources can, among other benefits, act as a substitute for fossil fuels, thereby reducing carbon dioxide emissions to the atmosphere, and also decrease EU dependence on foreign energy imports (Berndes and Hansson 2007).

The development of renewable energy sources has been substantially supported at the EU level by Directive 2009/28/EC of the European Parliament and the Council of 23 April 2009. According to this Directive, Poland is obliged to obtain at least 15% of its energy from renewable sources in its gross final consumption of energy by 2020. In 2013, the share of renewable energy sources in the overall primary energy production in Poland amounted to 11.9% and was generated mainly from solid biofuels

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(76.6%), including wood, waste wood, and wood residues (GUS 2015).

Directive 2009/28/EC has been incorporated into Polish law by the Act on Renewable Energy Sources, which was adopted by the Parliament on 20 February 2015 (Ustawa 2015). The Act imposes considerable restrictions on the use of the so-called full-value wood, which is more useful for purposes other than energy production. As a result, a special support system has been set up that is dedicated to renewable energy producers. The latter may be granted tradable 'green certificates' if the generated energy entirely or partially comes from renewable energy sources. The green certificates may be traded with other energy producers who cannot fulfil their obligation to generate energy in a sustainable way. The scheme encompasses a range of renewable fuels including wood that is not classified as 'full-value wood' (which is strictly defined in the Act); suitable wood for use as a renewable energy source includes that derived from trees grown in short- and medium-rotation plantations on agricultural land.

Under Polish conditions, such plantations are managed on short cycles, usually 1–10 years (the time interval between felling), or medium rotations (the interval between planting and replanting) of 15–25 years (Zajączkowski 2013), using genera such as willow (*Salix* L.) and poplar (*Populus* L.) (Herve and Ceulemans 1996; Verwijst 2001; Stolarski 2009; Benetka et al. 2014) and, recently, black locust (*Robinia pseudoacacia* L.) (Lambert et al. 2010; Wojda et al. 2015). Many researchers also recommend growing such species (especially poplars) on cycles no shorter than 5–6 years (Fang et al. 1999; Alig et al. 2000; Boelcke and Kahle 2000). According to Zajączkowski (unpublished data), poplars produce the highest yield among other fast-growing species in Polish conditions under a short-rotation coppice (SRC) regime. One of the basic conditions for such plantations to be profitable is to use cultivars with known productivity. In Europe, including Poland, several poplar species and their hybrids are used to grow energy wood. They generally belong to one of two sections of the *Populus* genus, either the *Aigeiros* section (black poplars) or *Tacamahaca* section (balsam poplars) (Zajączkowski and Wojda 2012). S. *Aigeiros* contains the species *P. deltoides* Bart. Ex Marsh, *P. fremontii* S.Watson, and *P. nigra* L. while s. *Tacamahaca* includes *P. angustifolia* E.James, *P. balsamifera* L., *P. maximowiczii* Henry, and *P. trichocarpa* Torr. & A.Gray ex Hook. Considerable breeding efforts have produced a number of fast-growing poplar cultivars (Stanton et al. 2010; Karp et al. 2011); these are derived almost entirely from inter-specific crosses (Benetka et al. 2014). In Europe, new poplar hybrids are mainly derived from crosses between the s. *Aigeiros* species *P. deltoides* and *P. nigra*, and called *P.* × *canadensis* Moench (Bisoffi and Gullberg 1996), or between the s. *Aigeiros* species *P. nigra* with the s. *Tacamahaca* species *P. maximowiczii* (Stanton et al. 2010). In Poland, there is a long tradition of growing hybrid NE-42 (known in Poland as 'Hybrida 275') that was produced from the s. *Tacamahaca* species cross *P. maximowiczii* × *P. trichocarpa*. This inter-species hybrid has been tested on many occasions in long- and medium-rotation forestry plantations (Zajączkowski and Wojda 2012), as has an intra-specific hybrid of *P. trichocarpa* called 'Fritzi Pauley'. In SRC systems, resprouting capacity is critical for biomass production in consecutive rotations until the end of productive life (rotation age) of a given plantation; productive abilities of the cultivars are also important, as is the length of the productive cycle (time from planting to first felling or between felling events).

The aim of this study was to evaluate the use of 10 selected poplar cultivars from the *Aigeiros* and *Tacamahaca* sections in short felling cycles for energy purposes and to compare the biomass yields of these cultivars. Additional aims were to preliminarily identify a suitable cycle length and preliminarily evaluate the sprouting capacity of various cultivars under the climatic conditions of northern Poland.

Methods

Location and climatic conditions

The experiment was carried out in northern Poland (N 54° 4′ 26″, E 20° 30′ 4″). According to the physical and geographic divisions of Poland (Kondracki 2011), the experimental area was located within Eastern Europe, in a subarea of the East European Lowland, within the East Baltic-Belarusian Province. The mean annual temperature of the study area was 7.6 °C. Annual rainfall was approximately 626 mm, and the growing season was approximately 200 days. According to the IUSS Working Group WRB (2015), the main type of soil on the research area is Cambisol. The study location was selected because it experiences the most severe climatic conditions for forest and agricultural production in Poland. By testing the productivity of the analysed cultivars in unfavourable conditions, a benchmark for the potentially lowest plantation yields was obtained.

Cultivars

Planting material was produced from woody cuttings of 10 cultivars as shown in Table 1.

Layout, establishment, and tending

The experimental area for the study was established in April 2010 on post-agricultural land covering 5.91 ha. Poplar saplings were planted in holes, created by an earth auger powered by a tractor, with spacing of 2.5 × 3 m (1333 plants ha^{-1}). The experimental area was fenced to prevent browsing by wild animals.

Table 1 Source and parentage of the poplar cultivars used

Cultivar name	Parent 1	Section of *Populus* genus	Parent 2	Section of *Populus* genus	Sex	Source
'AF-8'	*P.* × *generosa* (a cross between *P. deltoides* and *P. trichocarpa*	s. *Aigeiros* for *P. deltoides* and s. *Tacamahaca* for *P. trichocarpa*	*P. trichocarpa*	s. *Tacamahaca*	♀	Alasia Franco Vivai, Savigliano, Italy
'AF-6'	*P.* × *generosa* (a cross between *P. deltoides* and *P. trichocarpa*)	s. *Aigeiros* for *P. deltoides* and s. *Tacamahaca* for *P. trichocarpa*	*P. nigra*	s. *Aigeiros*	♀	Alasia Franco Vivai, Savigliano, Italy
'AF-2'	*P. deltoides*	s. *Aigeiros*	*P. nigra*	s. *Aigeiros*	♂	Alasia Franco Vivai, Savigliano, Italy
'MON' = 'Monviso'	*P.* × *generosa* (a cross between *P. deltoides* and *P. trichocarpa*)	s. *Aigeiros* for *P. deltoides* and s. *Tacamahaca* for *P. trichocarpa*	*P. nigra* (*P. nigra* × *P. nigra*)	s. *Aigeiros*	♀	Alasia Franco Vivai, Savigliano, Italy
'Albelo'	*P. deltoides*	s. *Aigeiros*	*P. nigra*	s. *Aigeiros*	♂	Luis Poloni, Nerac, France
'Degrosso'	*P. deltoides*	s. *Aigeiros*	*P. nigra*	s. *Aigeiros*	♂	Luis Poloni, Nerac, France
'Polargo'	*P. deltoides*	s. *Aigeiros*	*P. nigra*	s. *Aigeiros*	♀	Luis Poloni, Nerac, France
'Koster'	*P. deltoides*	s. *Aigeiros*	*P. nigra*	s. *Aigeiros*	♂	Luis Poloni, Nerac, France
'Fritzi Pauley'	*P. trichocarpa*	s. *Tacamahaca*	*P. trichocarpa*	s. *Tacamahaca*	♀	Brzeg Forest District, Poland
'NE-42' syn. 'Hybrida 275' or 'OP-42'	*P. maximowiczii*	s. *Tacamahaca*	*P. trichocarpa*	s. *Tacamahaca*	♂	Brzeg Forest District, Poland

The study layout was a randomised complete block design with three block replicates. Cultivars were randomly assigned to plots within each block. One hundred saplings (10 × 10) of a given poplar cultivar were planted within each plot. Bordering rows were planted around the experimental area. During the first 2 years, the plantation was weeded once per year. After 5 years of growth, 20 trees of each block of 100 were harvested (in early spring 2015). Two rows of trees were cut in each plot from the north side, while retaining the bordering rows. One year later, resprouting capacity of the stumps was assessed. At the same time (early spring 2016), 20 more trees per plot were cut.

Analysis of growth parameters of individual trees at 5 and 6 years old was performed for the same 80 trees per plot. We cut 20 trees from each plot (20% of all trees in the plantation) after 5 years of growth to determine the sprouting capacity and length of shoots from the stump at 1 year after felling (to evaluate sprouting capacity in the second 5-year cycle).

Measurement

Measurements and determinations were performed on 5-year-old trees (5-year cycle) and repeated on the same trees 1 year later (6-year cycle), in early spring in the years 2015 and 2016, respectively.

The survival rate was based on the number of living trees. Diameter at breast height (DBH; measured at a height of 1.3 m) of all trees was measured in millimetres. Heights (cm) were recorded for 20 trees in each plot. The height curve was constructed separately for each cultivar in a given block, according to the following function (Näslund 1936):

$$H = \left(\frac{\mathrm{DBH}}{\alpha + \beta * \mathrm{DBH}}\right)^2 + 1.3 \qquad (1)$$

where
H tree height (m),
DBH diameter at breast height (cm), and
α, β fitted coefficients.

The estimated coefficients (α, β) of the regression function for each cultivar in each block were used to estimate the height of trees from the entire range of DBH and, as a result, to define an average height for cultivars.

Twenty trees were cut in early spring in 2015, and their length and thickness were measured in order to evaluate tree weight for the 5-year cycle. Fresh-weight biomass of these trees was recorded (to the nearest 1 g). In 2016, after measurement of growth parameters (see above), 20 more trees per plot were cut in order to evaluate 6-year-old trees. The basal area of all trees was used to identify an 'average tree' for each cultivar in a given block (replicate). The 'average tree' samples were used to evaluate the per cent share of above-ground dry matter (DM) for each cultivar. The cross-sectional areas of the average trees were measured at the middle of every 2-m section and their fresh biomass determined by weighing 20-cm-long bolts from the middle of every 2-m section. Trunk and branch samples were taken from each replicate and weighed separately. The size of these samples ranged from 6284 to 7004 g, depending on the thickness of the trees. The 'average tree' samples were dried at 105 °C until their weights stabilised. The per cent share of DM was estimated as the ratio of the dry mass of samples to their fresh biomass (for each tree separately). Total DM yields per unit area were determined from the weight of harvested fresh biomass obtained from a given replicate multiplied by the appropriate value for the per cent DM and calculated for a given unit area (ha) per year, taking plant survival rate into account.

During the second 5-year cycle, heights of 1-year-old shoots regrowing from the 20 stumps in each plot were measured, using the tallest shoot of each stump. The number of shoots more than 50 cm in length was counted for each stump.

Statistical analysis

Statistical analyses were performed to test the significance of differences between averages of the following dependent variables: DBH, height, and estimated dry mass of trees grown on 5-year and 6-year cycles and shoot height and number of shoots per stump after 1 year of growth during the second 5-year cycle.

Analysis of variance (ANOVA) was performed using the following model:

$$y_{ijk} = \mu + \alpha_i + \beta_j + e_{ij}$$

where
y_{ijk} dependent variable,
μ mean,
α_i clone fixed effect,
β_j block fixed effect, and
e_{ijk} random test error.

The basic assumptions within the model were tested before carrying out the ANOVA. The tested assumptions were the normal distribution of the variables (using the Kolmogorov–Smirnov test [$\alpha = 0.05$]) and the homogeneity of variances (using Levene's test [$\alpha = 0.05$]). When the ANOVA indicated significant inter-cultivar differences, Tukey's HSD test was used ($\alpha = 0.05$). Biomass production of cultivars growing on 5-year and 6-year cycles (t ha^{-1} year^{-1}) was compared using a contrast analysis ($\alpha = 0.05$).

The statistical analyses were performed using the statistical package Statistica 10.0 (StatSoft 2011).

Results

Survival rate

Six of the 10 cultivars tested had high survival rates (>90%) at both ages. Two cultivars ('AF2', 'AF8') had a survival rate of just under 90% (Table 2). However, cultivars 'AF-6' and 'MON' suffered extensive frost damage and showed high individual plant mortality (survival rate <50%). Accordingly, these two cultivars were excluded from further analysis.

DBH

The average (quadratic mean) DBH at 5 years of age for the eight cultivars analysed was 95.3 mm. The average (arithmetic mean) diameters of the various cultivars showed statistically significant differences. Cultivars 'NE-42' and 'Fritzi Pauley' had the largest mean DBH values (110.7 and 105.6 mm, respectively), which were significantly greater than the DBH values of other cultivars (Table 2). In contrast, the cultivar 'AF-8' had the lowest DBH at 62.6 mm.

As expected, the average (quadratic mean) DBH at 6 years of age in the eight cultivars was higher than that in the 5-year-old trees, i.e. 110.5 vs. 95.3 mm. As with the 5-year cycle, the 'NE-42' and 'Fritzi Pauley' cultivars had the highest mean DBH in the 6-year cycle and the lowest mean DBH was for 'AF-8' trees (74.6 cm) (Table 2).

Height

The average (quadratic mean) height for all eight cultivars analysed on a 5-year cycle was 9.48 m. In a similar manner to the analysis of DBH, the 'NE-42' and 'Fritzi Pauley' cultivars were the tallest at 10.4 and 10.2 m, respectively (arithmetic mean) (Table 2).

The average (quadratic mean) height for all eight cultivars analysed on a 6-year cycle had an average (quadratic mean) height of 10.8 m. The 'Fritzi Pauley' cultivar produced significantly taller trees (arithmetic mean 13.2 m), than all other analysed cultivars. Trees of the 'AF-8' cultivar had the lowest mean heights in both the 5- and 6-year cycles, of 7.6 and 8.4 m, respectively (Table 2).

Diameter and height increment

Knowledge of the growth dynamics of various cultivars could be helpful in selecting appropriate production-cycle lengths. The 'NE-42' and 'Fritzi Pauley' cultivars produced the largest trees on the 5-year cycle (Table 2). However, after one more year of growth (i.e. a 6-year cycle), the 'Fritzi Pauley' clone showed its genetic potential and achieved the greatest DBH increment (18.5 mm) among all cultivars as well as the largest height increment (3.0 m) and significantly exceeded all other cultivars for both metrics (Fig. 1). In comparison to 'Fritzi Pauley', the other cultivars were significantly inferior with respect to both of these growth characteristics, achieving annual DBH increments of 12.0 mm ('AF-8') to 16.8 mm ('Degrosso') and annual height increments of 0.5 m ('Degrosso') to 1.6 m ('NE-42') (Fig. 1).

Table 2 Average survival, DBH, and height (H) comparison of the eight cultivars analysed in 5- and 6-year cycles

Cultivar	After 5 years					After 6 years				
	Survival rate (%)	DBH (mm) Arithmetic mean	±SE	H (m) Arithmetic mean	±SE	Survival rate (%)	DBH (mm) Arithmetic mean	±SE	H (m) Arithmetic mean	±SE
'AF-8'	89	62.6^{e}	1.2	7.55^{d}	0.09	89	74.6^{e}	1.4	8.40^{g}	0.09
'AF-2'	88	93.7^{bc}	1.8	9.39^{b}	0.12	87	110.5^{bc}	1.8	10.17^{e}	0.09
'Albelo'	98	72.0^{d}	1.1	8.26^{c}	0.09	98	86.2^{d}	1.1	9.61^{f}	0.07
'Degrosso'	99	98.1^{b}	1.6	9.63^{b}	0.10	99	114.9^{b}	1.5	10.17^{de}	0.08
'Polargo'	99	90.1^{c}	1.3	9.36^{b}	0.09	99	105.4^{c}	1.4	10.70^{c}	0.09
'Koster'	97	95.8^{bc}	1.8	9.56^{b}	0.12	97	111.1^{bc}	1.9	10.54^{cd}	0.11
'Fritzi Pauley'	96	105.6^{a}	1.5	10.18^{a}	0.10	96	124.1^{a}	1.6	13.16^{a}	0.08
'NE-42'	99	110.7^{a}	1.5	10.44^{a}	0.09	99	124.9^{a}	1.4	12.04^{b}	0.11
Quadratic mean (global)		95.3		9.48			110.5		10.80	
Arithmetic mean (global)		91.4		9.32			106.8		10.63	

The same superscript letters indicate statistically homogenous groups (Tukey's HSD test, $\alpha = 0.05$)

Single-tree dry mass

The largest DM in the 5-year cycle was recorded for an 'NE-42' tree (28.9 kg), which was significantly greater than those of the other seven cultivars. The DM values for the 'Fritzi Pauley' (20.4 kg), 'Koster' (18.7 kg), and 'Polargo' (18.2 kg) cultivars were statistically homogeneous. In contrast, the dry mass of the single tree of cultivar 'AF-8' in the 5-year cycle was significantly lower at 7.2 kg (Table 3).

After 6 years of biomass production, the highest calculated DMs for a single tree were 35.2 and 32.4 kg for cultivars 'NE-42' and 'Fritzi Pauley', respectively. The lowest mass calculated for a single tree was that of 'AF-8' (13.2 kg) (Table 3).

Biomass production

Biomass production data are provided in Table 3 and Fig. 2 and show large differences among cultivars. Notably, there was an improvement in the productivity of 'Fritzi Pauley' between the 5- and 6-year cycles of 5.2 and 6.9 t ha^{-1} year^{-1}, respectively. The 'AF-8' cultivar had the lowest biomass productivity (2.6 t ha^{-1} year^{-1}) among all eight cultivars analysed (Table 3 and Fig. 2).

Height and number of shoots during the second cycle

An ANOVA of the number of 1-year-old shoots growing from stumps of trees harvested after 5 years of growth showed significant variation among cultivars. The 'NE-42', 'Fritzi Pauley', and 'Koster' cultivars formed a group that produced the largest number of shoots. The lowest

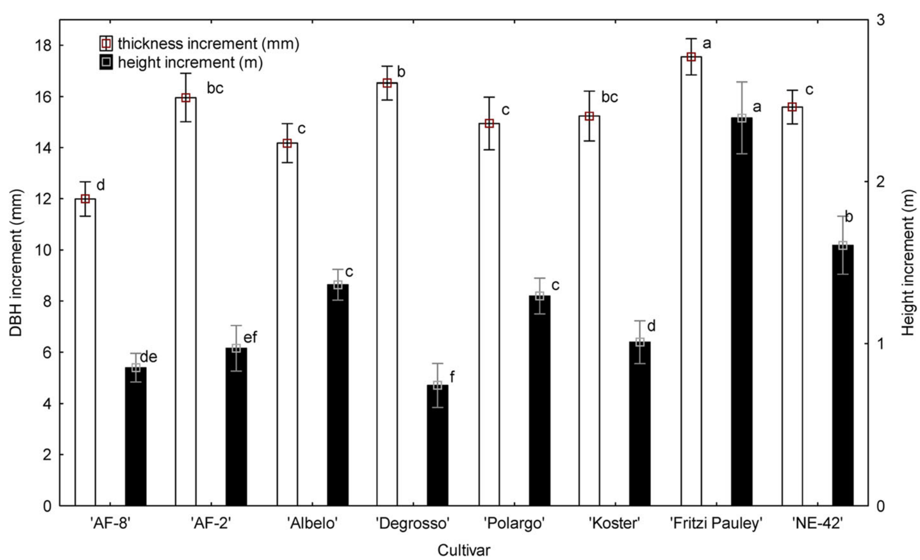

Fig. 1 Annual calculated DBH and height increments (±SE) of eight poplar cultivars at age 5 years in 2015. Different *lowercase letters* between columns indicate statistical differences ($p < 0.05$) (Tukey's HSD test)

Table 3 Dry matter (DM) values of analysed cultivars, based on surviving individuals

Cultivar	5-year cycle				6-year cycle			
	DM of a single tree (kg)	±SE	DM (t ha^{-1} $year^{-1}$)	±SE	DM of a single tree (kg)	±SE	DM (t ha^{-1} $year^{-1}$)	±SE
'AF-8'	7.23[d]	0.55	1.71[d]	0.15	13.18[e]	0.82	2.60[e]	0.18
'AF-2'	12.19[c]	0.83	2.86[c]	0.22	18.95[cd]	1.15	3.70[cd]	0.26
'Albelo'	12.41[c]	0.98	3.23[c]	0.26	16.16[de]	0.93	3.50[de]	0.21
'Degrosso'	13.57[c]	0.81	3.57[c]	0.22	21.84[bc]	1.09	4.79[bc]	0.24
'Polargo'	18.21[b]	0.97	4.81[b]	0.26	23.83[bc]	1.10	5.25[bc]	0.24
'Koster'	18.72[b]	1.03	4.82[b]	0.28	25.46[b]	1.41	5.47[b]	0.31
'Fritzi Pauley'	20.41[b]	1.17	5.24[b]	0.31	32.41[a]	1.23	6.93[a]	0.27
'NE-42'	28.85[a]	1.25	7.63[a]	0.33	35.17[a]	1.44	7.75[a]	0.32

The same superscript letters indicate statistically homogenous groups (Tukey's HSD test, $\alpha = 0.05$)

numbers of shoots were produced by cultivars 'AF-8' and 'AF-2' (Table 4).

ANOVA also identified statistically significant differences for shoot lengths; however, the ranking was different to that of shoot number. The 'Degrosso', 'Albelo', 'AF-8', 'NE-42', and 'Fritzi Pauley' cultivars formed a group that produced the longest shoots while the 'Koster' and 'Polargo' cultivars had the shortest shoots (Table 4).

Discussion

There is a growing body of research on the use of poplar wood from short-rotation plantations as an energy resource in southern and western Europe (Spinelli et al. 2009; Aravanopoulos 2010; Gonzalez-Garcia et al. 2010). However, neither accumulation of timber volume nor sprouting ability in various poplar cultivars has been well studied with respect to climate conditions in Poland (Szczukowski and Stolarski 2013; Niemczyk et al. 2016).

The results of the present study suggest that cultivars 'NE-42' and 'Fritzi Pauley' had not only the best DBH and height but also the highest biomass production. Conversely, cultivar 'AF-8' had the lowest growth figures of those analysed. The 'AF-6' and 'MON' cultivars suffered from frost damage and high mortality, so they should not be grown for energy purposes in Poland because of their poor growth under the prevailing climatic conditions. A previous study by Zajączkowski et al. (unpublished data) showed that cultivar 'Fritzi Pauley' produces good biomass yields after 4 years when grown on a 4-year cycle in south-western Poland. Climatic conditions

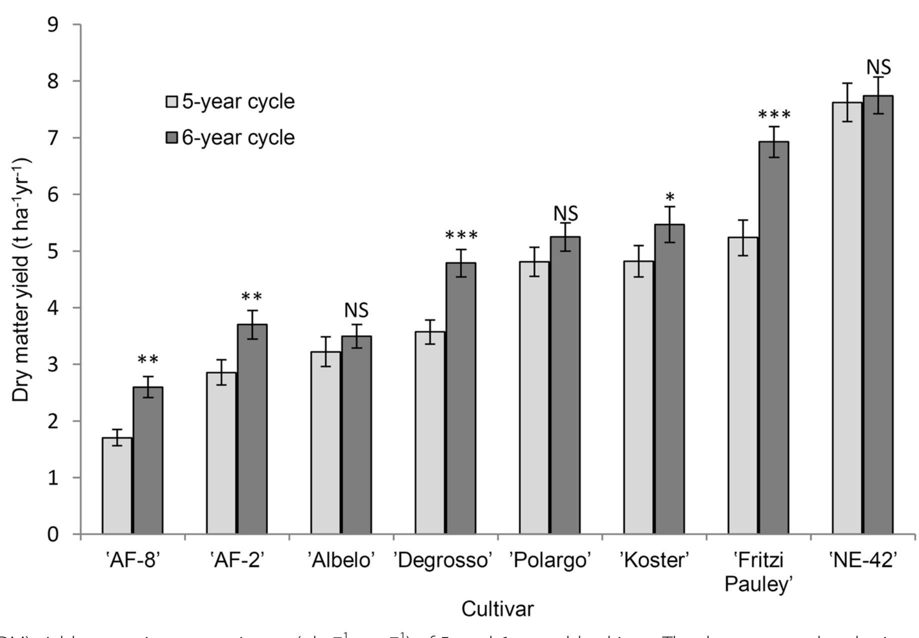

Fig. 2 Dry matter (DM) yield comparison per unit area (t ha^{-1} $year^{-1}$) of 5- and 6-year-old cultivars. The data were analysed using a contrast analysis. *NS* non-significant difference ($p > 0.05$); *significant difference ($p < 0.05$); **$p < 0.01$; ***$p < 0.001$

Table 4 Mean lengths and number of shoots per stump after the first year of the second 5-year cycle

Cultivar	Length (m)	±SE	Number	±SE
'AF-8'	2.09^{ab}	0.08	9.8^{e}	0.7
'AF-2'	1.92^{b}	0.10	12.4^{de}	0.8
'Albelo'	2.12^{ab}	0.08	14.6^{cd}	0.7
'Degrosso'	2.31^{a}	0.09	16.1^{bc}	0.7
'Polargo'	1.84^{bc}	0.05	16.7^{bc}	0.5
'Koster'	1.56^{c}	0.06	18.3^{ab}	0.5
'Fritzi Pauley'	2.02^{ab}	0.07	19.2^{a}	0.3
'NE-42'	2.03^{ab}	0.06	19.6^{a}	0.2

The same superscript letters indicate statistically homogenous groups (Tukey's test, $\alpha = 0.05$)

are milder in this location compared to the current study, and a biomass yield of approximately 8 – 9 t DM ha^{-1} year^{-1} was obtained.

Studies conducted in similar climatic conditions in other countries of central and eastern Europe showed similar or lower biomass productivity in poplar clones compared to the current work. For example, Lazdina et al. (2014) investigated growth rates in the Italian cultivars 'AF-2', 'AF-6', and 'AF-8' in Latvia (north-east of Poland) on a 3-year-cycle coppice system. Annual fresh biomass production (FM) was 6.62 t FM ha^{-1} for 'AF-6', 3.34 t ha^{-1} for 'AF-2', and 2.66 t ha^{-1} for 'AF-8'. These rates equate to biomass production of 2.71 t DM ha^{-1} for 'AF-6', 1.36 t ha^{-1} for 'AF-2', and 1.09 t ha^{-1} for 'AF-8' using a rate/share of DM (%) of 41% (Niemczyk et al. 2016). Interestingly, the 'AF-6' cultivar had relatively good productivity in that study but did very poorly in the current study. Benetka et al. (2014) compared the productivity of four local cultivars in a study conducted in the Czech Republic, south-west of Poland, using the 'NE-42' cultivar as a control. The 'NE-42' cultivar produced 8.3 t DM ha^{-1} year^{-1} during the first cycle under the most favourable site conditions. Each succeeding cycle (from the four employed) produced even higher yields, i.e. 15.4, 18.9, and 15.9 t ha^{-1} year^{-1}, respectively. Importantly, 'NE-42' was highly productive regardless of soil conditions. Such high productivity could be due to the exceptional adaptive capacities of this cultivar, which was selected from several thousand seedlings derived from planned crosses over 80 years ago (Stout and Schreiner 1933) and was one of 27 Schreiner and Stout crosses that were introduced to Poland in 1938. Interest in this cultivar increased during the 1950s because of its high resistance to disease and pests (Bugała 1973), and it is currently among the primary poplar cultivars recommended for use in Polish plantations (Zajączkowski and Wojda 2012).

Higher yields than those obtained in the current study could potentially be achieved from plantations in more favourable climatic conditions, such as in southern Europe. Yields could also be obtained more quickly since cycle length is one of the most important economic aspects of the production process (Armstrong et al. 1999; Nassi o Di Nasso et al. 2010). For example, biomass production in Italy averaged 9.9 t ha^{-1} year^{-1} for 1-year cycles and 16.4 t ha^{-1} year^{-1} for 3-year cycles (Nassi o Di Nasso et al. 2010). Similar average dry-mass yields (13.9 t ha^{-1} year^{-1}) were obtained from two poplar plantations with 3- and 6-year cycles in northern Italy (Manzone and Calvo 2016). However, Sabatti et al. (2014) found that biomass production differed significantly among consecutive biennial coppice cycles for six various poplar genotypes in Italy. In the first cycle, biomass production amounted to 16 t ha^{-1} year^{-1}, peaked at 20 t ha^{-1} year^{-1} in the second, and decreased to 17 t ha^{-1} year^{-1} in the third cycle. The highest biomass production was found, inter alia, for the 'Monviso' and 'AF-8' cultivars with mean annual dry-mass production of 19.5 and 19.3 t ha^{-1} year^{-1}, respectively. Conversely, cultivar 'AF-8' had the lowest biomass productivity (2.6 t ha^{-1} year^{-1}) in the current study and the 'Monviso' cultivar was excluded from our experiment because of poor tolerance to the severe climatic conditions of northern Poland.

A study in Poland found that biomass production from one 4-year cycle was higher than that from two 2-year cycles combined (Zajączkowski et al., unpublished data). These results confirm the conclusions of Armstrong et al. (1999) and Nassi o Di Nasso et al. (2010), which stated that average production increases when poplar plantations are grown on longer cycles. Many researchers recommend cycles no shorter than 5–6 years (Fang et al. 1999; Alig et al. 2000; Boelcke and Kahle 2000). The average yield (in t ha^{-1} year^{-1}) of five of the eight cultivars analysed increased significantly with a 6-year cycle compared with a 5-year cycle. However, defining the optimal rotation length of energy poplar plantations under Polish climatic conditions will require further research and exploration of even longer cutting cycles. In addition, the sprouting capacity of the currently tested cultivars is important as it contributes to the economic efficiency of subsequent cycles until the end of biomass production in a given plantation.

Significant differences were observed in shoot regrowth from stumps of different cultivars after the first year of the second 5-year cycle. The 'NE-42', 'Fritzi Pauley', and 'Koster' cultivars produced the largest number of shoots. The first two are crosses of *P. trichocarpa*, and their growth abilities can be linked to the developmental characteristics inherited from this species. However, the resprouting ability of the 'Koster' cultivar, which is a cross between *P. deltoides* and *P. nigra*, is harder to explain. Benetka et al. (2014) indicated that poplar clone selection should focus on the production of thick, strong shoots, rather than a large number of weaker shoots. Shoot thickness was not measured in the current study, but the 'Degrosso', 'Albelo', 'AF-8', 'NE-42', and 'Fritzi Pauley' cultivars produced the longest shoots. The 'NE-42' and 'Fritzi Pauley' cultivars produced large numbers of relatively long shoots, so these two cultivars are likely to be the most useful for biomass production in either short or medium cycles. However, the final rating, which will evaluate total biomass production of a given cultivar, will not be made until the end of biomass production over three harvesting cycles and the evaluation of an optimal cycle length in the climatic conditions of northern Poland.

Conclusions

The Italian cultivars 'AF-6' and 'Monviso' did not adapt to the local climatic conditions, and the productivity of other Italian clones was poor. In the 5-year cycle, the 'NE-42' cultivar produced the highest amount of biomass among the eight cultivars analysed. However, the 'Fritzi Pauley' cultivar also demonstrated a high biomass production potential in a 6-year cycle. In addition, both of these cultivars had the benefit of producing many long shoots after the first year of growth in the second 5-year cycle.

The length of the production cycle is important for biomass accumulation in energy plantations. Our preliminary results indicate that five of eight cultivars analysed gave higher biomass productivity over a 6-year cycle than over a 5-year cycle.

Overall, the results of the present study indicate the need to test cultivars in local climatic conditions before deploying them on a commercial scale.

Abbreviations

DBH: Diameter at breast height; DM: Dry matter; FM: Fresh biomass production; SRC: Short-rotation coppice

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Authors' contributions

MN was the primary author, undertook the technical design of the study, data collection, and data analysis, and contributed to writing the manuscript. TW contributed to the technical design of the study, data collection, and revisions of the manuscript. AK contributed to writing the manuscript. All authors have agreed to the authorship and the order of authorship for this manuscript; and all authors have the appropriate permissions and rights to the reported data. All authors read and approved the final version of the manuscript.

Competing interests

The authors declare that they have no competing interests.

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