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Biomass yield and energy efficiency of willow depending on cultivar, harvesting frequency and planting density

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Abstract: The study aimed at comparing the yield of dry biomass and energy efficiency of 22 willow cultivars depending on the harvesting frequency and variable plant density. The field experiment was established in 2010. The willow cultivars were planted in two densities; 13 300 and 32 500 plants per ha. Among the compared cultivars in the second year (2013) of full production, high yield of dry matter was obtained from cvs. Tordis (33.1 t/ha/year), Inger (30.4 t/ha/year) and Klara (29.0 t/ha/year). After six years of cultivation, the highest aboveground dry matter was given by cvs. Tora (27.4 t/ha/year) and Tordis (27.0 t/ha/year). The gross calorific value of willow biomass ranged from 15.2–20.1 GJ/t dry weight. Greater energy efficiency (329.3 GJ/ha/year) occurred in willow cultivars collected in a two-year cycle than in the one-year cycle (286.4 GJ/ha/year). In the two-year cycle collected in the third year after planting, energy efficiency was greater (379.5 GJ/ha/year) than in the two-year cycle harvested in the sixth year after planting (279.15 GJ/ha/year). The initial slower growth of biomass does not determine plant yielding.

Keywords: willow biomass production; *Salix* spp.; energy crop; harvest rotation; renewable energy source

Limited resources of conventional fuels and increasing demand for energy are forcing the intensification of the use of renewable energy sources. One of such carriers, producing the best results under the conditions of Polish climate is energy biomass obtained from *Salix* spp. characterized by a rapid growth, cultivated in short rotations (Szczukowski et al. 2005, Lipiński and Żejmo 2012, Owoc and Walczyk 2013). Biomass production and use are characterized by low costs of its obtaining, high net calorific value, low atmospheric pollutant emissions and capacity to recultivate the soils by certain species of energy crops. The multi-annual plantations of energy crops contribute to the reduction of soil erosion, they can be used in recycling of the organic wastes and reduce the demand for wood from natural forests (Adegbidi et al. 2001, Labrecque and Teodorescu 2001, 2005, Isebrands et al. 2014). Examples of the use of short-rotation willow coppice in phytoremediation systems for treating different kinds of waste in Sweden are presented by Dimitriou and Aronsson (2005). Apart from the environmental benefits and the use for energy purposes, the willow fiber is applied in the cellulose and paper industry (Makkonen et al. 2000, Cerrillo et al. 2015). In Poland, the demand for biomass for energy purposes is very high. It has been estimated that to obtain the 15% share of renewable source-based energy in the total energy balance until 2020, approximately 17.5 million tons of dry biomass should be obtained per annum (Grzybek 2004). As reported by Weger et al. (2016) in the Czech Republic, short rotation coppice plantations can grow in the future on an area of about 120 000 hectares. Studies indicate that perennial plants producing lignin-cellulose biomass, such as willow, enable obtaining better yields for energy purposes than typical agricultural crops (Börjesson 1996). A series of studies demonstrate that the biomass yield is influenced by number of significantly related factors. In the production of willow biomass for energy purposes, the density of plants per unit area in the whole period plays an important role,

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most often it is a 25-years cycle of cultivation. The currently known results indicate that the optimum plant density should be from 15 000 to 25 000 shoot cuttings per ha depending on the habitat conditions, cultivar or clone of willow (Bergkvist and Ledin 1998, Bullard et al. 2002, Wilkinson et al. 2007). With dense plantings, willow exhibits capacity to regulate the stem density; thus a certain portion of stems wither while the remaining ones accumulate more dry weight (Verwijst 1991). Bergante et al. (2010) have shown that densities of 10 000 plants per ha may increase the biomass yield during the first 2-year cycle with respect to 8 000 plants per ha, and a minimum survival percentage of 80% is recommendable to avoid yield losses. However, Djomo et al. (2015) based on the analysis of research carried out in many EU countries, they found no correlation between the yield and planting density.

The study aimed at comparison of the yield of dry biomass and energy efficiency of 22 willow cultivars depending on the year of production and variable planting.

MATERIAL AND METHODS

Field experiment design. The six-year field experiment was established in a split-block design in two replications in spring 2010 at the Zdoo Śrem-Wójtostwo (52°04'N, 17°02'E) on a loamy silt Gleyic Fluvisol. Soil properties at the beginning of the experiment in the topsoil were as follows: sand 920 g/kg, silt 40 g/kg, clay 40 g/kg, pH_{KCl} 6.3, content of available P 34.9 mg/kg, K 43.1 mg/kg, Mg 34.1 mg/kg, Ca 1071.4 mg/kg. The soil granulometric composition was determined using the Cassagrande's method, pH by the potentiometric method, available forms of phosphorus and potassium by the Egner-Riehm method, magnesium by the Schachtschabel method and calcium by the Spurway method at the Chemical Agricultural Station in Krakow.

The course of the weather conditions (temperature and precipitation) is presented in Figure 1. In individual years beginning from 2010, the total sum of precipitation was 735, 413, 570, 536, 410 and 408 mm, respectively. Larger amounts of precipitation than

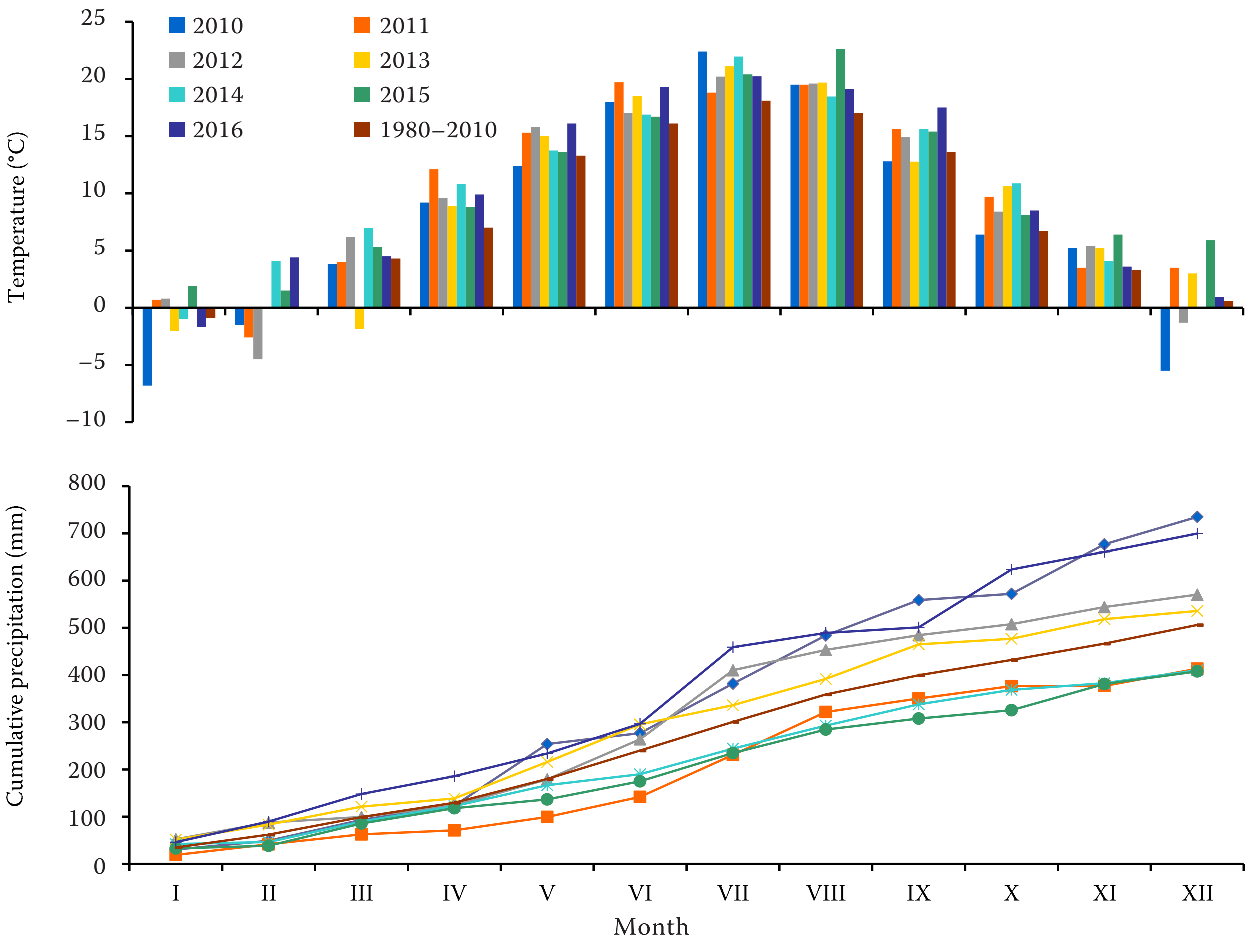

Figure 1. Weather conditions during the research compared to the long-term period

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the long-term average (506 mm) were recorded in 2010, 2012, 2013 and 2016. Particularly unfavourable phenomena related to the excessive amount of precipitation caused the Warta River floods occur in the following periods: 28.02.2010–15.04.2010, 21.05.2010–28.06.2010, 14.04.2013–16.05.2013 and 05.06.2013–20.07.2013. Shortage of precipitation and simultaneously high air temperatures were observed from April to June 2011 and in April and May 2016.

Following the harvest of the previous crop in 2009, permanent weed combat was performed with a total herbicide (Gallup 360 SL at the amount of 3 L/ha) and deep autumn ploughing was conducted. During the spring cultivation, mineral fertilization was applied at the amount of 8.7 kg P and 24.9 kg K per ha. Due to the good previous crop properties (lupin), nitrogen was not applied. The maintenance consisted primarily of mechanical weeding and supplementing the lacking plants. Every year after the start of the spring vegetation, mineral fertilization was applied at the following doses: N – 40 kg, P – 8.7 kg, K – 49.8 kg per ha.

The study covered a total of 22 willow cultivars, including 10 leading Swedish cultivars and 12 Polish cultivars. The cultivars were characterized in terms of botanical origin; in the case full description was lacking, they were classified as *Salix* ssp. (Table 1). The willow cuttings with a length of 22–25 cm and a diameter of 1.5–2.0 cm obtained from breeders of individual cultivars were planted in the third decade of April in two densities: 13 300 and 32 500 plants per ha. The row spacing and distance between cuttings in a row were for the densities: 1.0 × 0.75 m and 0.75 × 0.41 m, respectively. The plot size was 27 m^2.

In the first year after planting (March 2011) the cutting back was conducted. The harvests of stems was carried out in the third (February 2013), fourth (February 2014) and sixth (January 2016) year after planting. In the fourth year after planting a collection of annual stems was carried out due to large damages caused by ice and flooding water, causing significant lodging of the stems. The harvest from one-year of growth was justified by equalizing of the status of the entire experiment.

Plant sampling and analysis. In successive cycles, willows were harvested with a combustion-engine mower, at a fixed height of about 10 cm above the soil surface. After each harvest, the entire mass of stems from each plot was weighed (within an accuracy of 1 kg) and the fresh matter yield was determined in t/ha. Willow plants from each plot were chipped into chips with Skorpion 120SD chipper (Teknamotor Sp. z o. o., Ostrowiec Świętokrzyski, Poland) and representative samples (1–2 kg) were taken for laboratory analysis. Moisture of biomass was determined by a dry weight method at 105°C until a constant weight was obtained. The moisture content in biomass and fresh matter yield was then used to calculate dry matter yield.

Gross calorific value ($q_{p,gr,d}$) of the willow biomass was determined using the KL-12Mn calorimeter made by Precyzja-Bit, Poland (Bydgoszcz).

Table 1. Characteristics of willow cultivars used in researches

Cultivar	Breeder	Taxon
Dobkowska	PL, J.W. Dubas, Jelenia Góra	*Salix* ssp.
Gudrun	SE, Svalöf Weibull AB	*S. dasyclados*
Inger	SE, Svalöf Weibull AB	*S. triandra*, *S. viminalis*
Karin	SE, Svalöf Weibull AB	*S. viminalis* × *S. schwerinii*
Karolinka	PL, J.W. Dubas, Jelenia Góra	*Salix* ssp.
Kerim	PL, M.Maciocha/ Ekokom, Łódź	*S. viminalis*
Klara	SE, Svalöf Weibull AB	(*S. dasyclados*, *S. viminalis*, *S. schwerinii*)
Kortur	PL, UWM Olsztyn	*S. viminalis*
Linnea	SE, Svalöf Weibull AB	*S. viminalis* × *S. schwerinii*
Lisa	SE, Svalöf Weibull AB	*S. viminalis* × *S. schwerinii*
Marcel	PL, J.W. Dubas, Jelenia Góra	*Salix* ssp.
Monotur	PL, UWM Olsztyn	*S. viminalis*
Oltur	PL, UWM Olsztyn	*S. viminalis*
Paulinka	PL, J.W. Dubas, Jelenia Góra	*Salix* ssp.
Sprint	PL, UWM Olsztyn	*S. viminalis*
Start	PL, UWM Olsztyn	*S. viminalis*
Stina	SE, Svalöf Weibull AB	*S.aegyptiaca*, *S. schwerinii*, *S. viminalis*, *S. lanceolata*
Sven	SE, Svalöf Weibull AB	*S. viminalis* × *S. schwerinii*
Tora	SE, Svalöf Weibull AB	*S. viminalis* × *S. schwerinii*
Tordis	SE, Svalöf Weibull AB	*S. viminalis* × *S. schwerinii*
Tur	PL, UWM Olsztyn	*S. viminalis*
Turbo	PL, UWM Olsztyn	*S. viminalis*

PL – Poland; SE – Sweden

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The measurement consists of a complete combustion of a fuel sample (about 1 g) in an atmosphere of oxygen under pressure 2.5 MPa in a calorimeter, which was immersed in water. Measuring the temperature increase of water and using the formulas allows calculating the heat of fuel combustion. Net calorific value at a constant pressure ($q_{p,net,d}$) and net calorific value at 40% humidity ($q_{p,net,m}$) was calculated according to the equation (Eq. 1) provided in the study of Smaliukas et al. (2008).

$$q_{p,net,d} = q_{p,gr,d} - 2441\left(\frac{9H_2}{100}\right)\ (kJ/kg)$$
$$q_{p,net,d} = \frac{q_{p,net,d}(100 - W) - 2441 \times w}{100}\ (kJ/kg) \quad (1)$$

2441 – enthalpy of evaporation at 25°C; W – humidity 40%; H_2 = 6.2%.

Statistical analysis. The statistical calculations included analysis of variance for the split-block design in individual years of harvest with the separation of uniform groups using the Tukey's test and synthesis of averaged data of dry weight yield and energy value of the yield. Furthermore, principal component analysis was performed to determine the interaction between genotype and planting density for the dry weight yield. Calculations were carried out using Statistica 12 and Excel software.

RESULTS AND DISCUSSION

Dry biomass yield. Irrespective of the planting density, in annual terms, the yield of dry matter of stems of the tested cultivars ranged from 11.4 to 33.1 t/ha/year in the third year after planting, 6.6 to 23.0 t/ha/year in 2016, the fourth year after planting and from 7.2 to 27.4 t/ha/year in the sixth year after planting (Figure 2). In the third year after planting the highest yields of dry matter in the range from 28.2 to 33.1 t/ha/year were given by cvs. Tordis, Inger, Klara and Kortur. The cultivars with the lowest yield in the range of 15.0 to 11.4 t/ha/year were: Monotur, Karin, Gudrun and Karolinka. Yields of dry biomass collected in the fourth and sixth year after planting (2014 and 2016) were lower than in the third year after planting (2013) by an average of 27%. In the sixth year after planting (2016), the best yielding cultivars were Tora (27.4 t/ha/year), Tordis (27.0 t/ha/year), Inger (24.1 t/ha/year), Klara (20.2 t/ha/year) and Sven (19.8 t/ha/year). The lowest yields in the range from 11.8 to 7.2 t/ha/year were found in the Gudrun, Dobkowska and Karolinka cultivars. Tordis was the highest-yielding cultivar also in the studies conducted by Larsen et al. (2014) in five sites in Denmark. Cvs. Tora and Inger were characterized by lower dry matter yield, while the smallest by cvs. Stina and Linnea. Also in the fourth year after planting (2014) the following crops yielded the lowest: cv. Dobkowska (11.3 t/ha/year), cv. Gudrun (10.3 t/ha/year) and cv. Karolinka (6.6 t/ha/year), and the highest yields were given by cvs. Klara, Start, Linnea and Sven, whose yields of the dry biomass were 23.0, 22.3, 22.0 and 21.7 t/ha/year, respectively. In the third and fourth year after planting (2013 and 2014) a favourable influence of higher density on the yield size was noted and in the sixth year after planting (2016) a reversed relationship was observed (Figure 3). The group of cultivars yielding above average per 1 vegetation year includes 11 cultivars, of which the following four yielded above 30–40%: Tordis, Inger, Tora and Klara. Yet the cultivars reacted poorly to a change in the planting density. The Inger cultivar had better yields in conditions of increased density and cv. Tora with lower density. Wilkinson et al. (2007) found a higher productivity of the Tora cultivar at a density of 25 000 than at 10 000 and 15 000 pcs ha, which indicates a relationship between the yield of this cultivar and the place of cultivation. Cultivars with reaction similar to that of cv. Inger were: Kerim, Stina, Turbo, Sprint, Paulinka, Dobkowska, Monotur and Karolinka, whereas the remaining cultivars exhibited a reaction similar to the Tora cultivar (Figure 4).

Djomo et al. (2015) performed an analysis of 47 experiments carried out on the energy of willow and poplar in 11 European countries at a density between 1556–25 000 shoot cuttings per ha. Based on these studies, the authors determined that the optimum plant density should be approximately 10 000 shoot cuttings; however, at the plant density of 15 000 shoot cuttings the biomass yield was 13% higher. The conducted experiment demonstrated that at the density of over 15 000 shoot cuttings per ha, no significant correlation between the density and the biomass yield occurs. Wilkinson et al. (2007) indicated that plant density in the range between 10 000–15 000 plants per ha is sufficient for good yield. According to these authors, a yield growth at the density of 20 000–25 000 seedlings is low, thus they believe that density to be the limit value and preferred in the areas of northern England. Kopp et al. (1997) showed an increase in the yield of dry willow biomass with an increase density in the range of 15 000 to 37 000 pcs ha, although the differences were not always significant. Stolarski et al. (2017) reported

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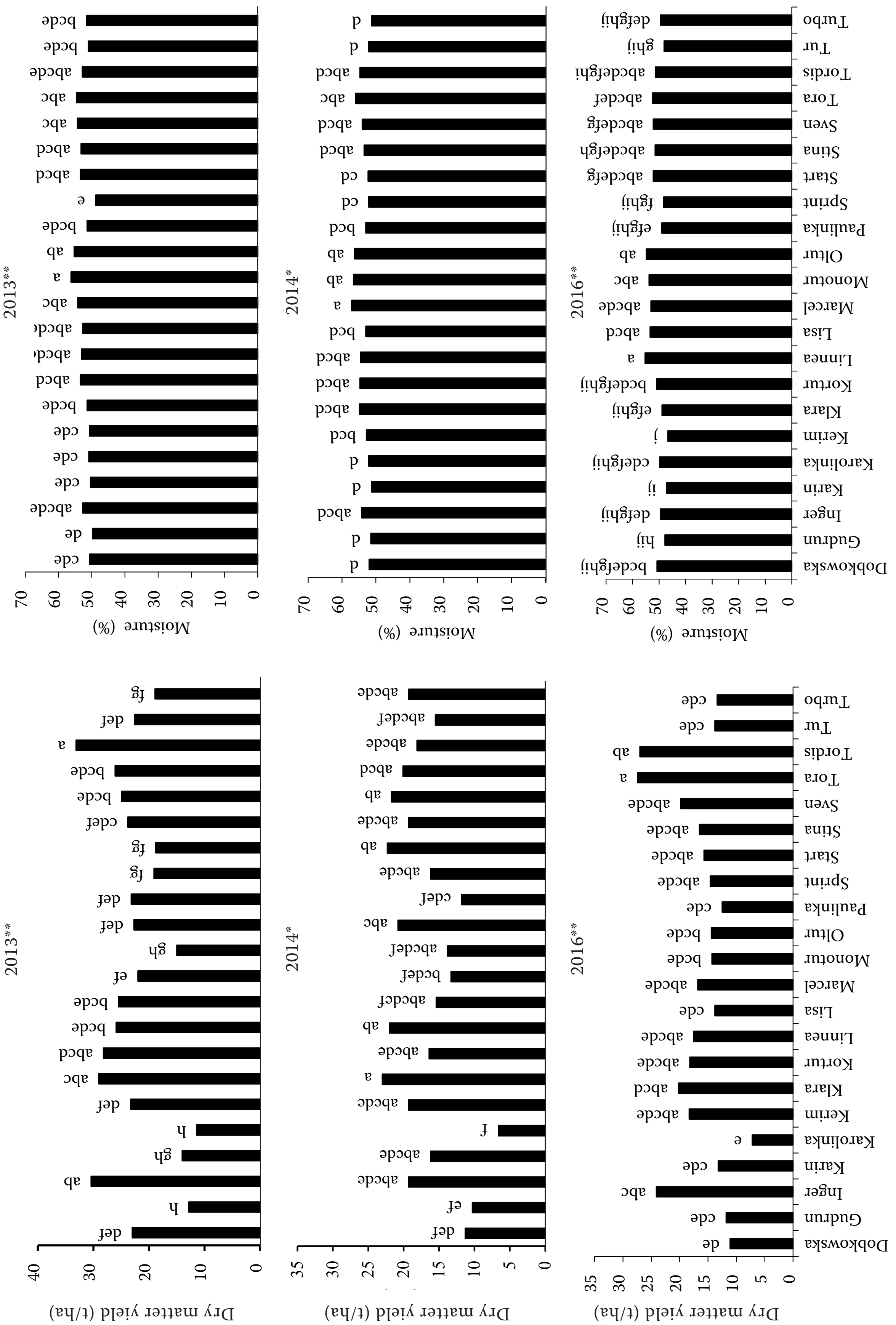

Figure 2. Dry matter yield and moisture of one-year (2014) and two-year willow shoots (2013 and 2016). *one year shoots; **two years hoots. Different letters indicate significant differences at P = 0.05

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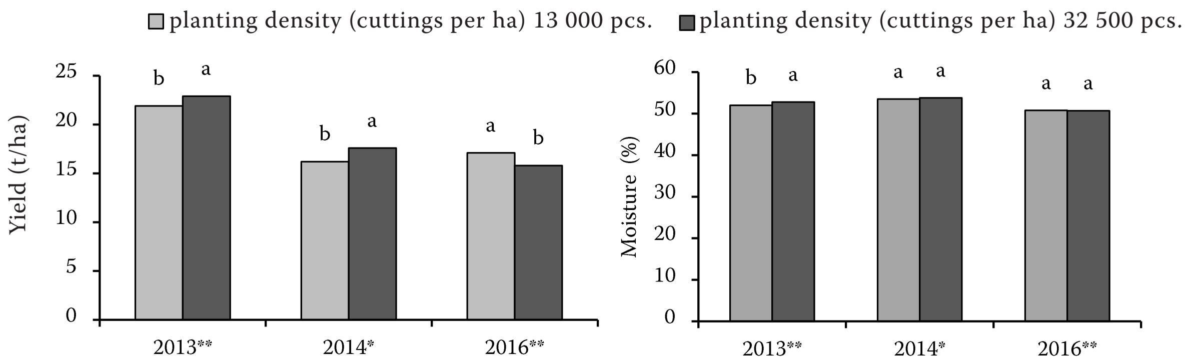

Figure 3. Yield of willow dry weight and moisture of willow shoots depending on plant density and years of harvesting. *one year shoots; **two years hoots. Different letters indicate significant differences at P = 0.05

a significant increase in dry biomass obtained only when the planting density increased from 12 000 to 24 000 pcs ha. Another increase in the planting density to 48 000 pcs/ha caused a decrease in the average yield of 6% compared to the 24 000 pcs/ha. In these studies, willow clones belonging to *S. viminalis* were characterized by higher efficiency of dry biomass than *S. dasyclados* genotype. This was confirmed in the study of Smaliukas et al. (2008), yet, only in the first two years of vegetation. With a three-year harvesting cycle, the yields were similar and with a four-year cycle *S. dasyclados* had greater yields than *S. viminalis*. Studies conducted by these authors further indicate that an increase in the yield in the following years of rotation primarily stemmed from a considerable increase in the *S. dasyclados* stem diameter, and to a lesser degree of the number of stems and their length. Szczukowski et al. (2005) compared yields of different willow species in the conditions of northern Poland. The highest yields were given by *S. viminalis* var. *lanceolata* and var. *Regali*, and the lowest by *S. triandra*. Cultivars with a high share of interaction with the factor objects are located close to its vector whereas those located close to the OX (abscissa) coordinate axis have lower reaction to the agronomic factor (Figure 5). In the discussed experiment, in conditions of low plant density, the highest yields were recorded in cultivars of the *S. viminalis* × *S. schwerinii* taxon (Tora, Sven, Lisa and Linnea, to a lesser degree Tordis), whereas the Inger cultivar (*S. triandra* × *S. viminalis*) yielded particularly high at a high density. The Polish cultivars of *S. viminalis* are medium-yielding, whereas the cultivars included in the genus *Salix* with unidentified systematic assignment yielded rather poorly and typically at a higher plant density. However, one should pay attention to the study of Smaliukas et al. (2008), who, by prolonging the harvest cycle to 4 years obtained an advantage of the *S. dasyclados* genotypes over *S. viminalis*. However, in the studies of Bullard et al. (2002), yield of *S. viminalis* dry biomass was by 2.7 t/ha/year higher than *S. × dasyclados*. According

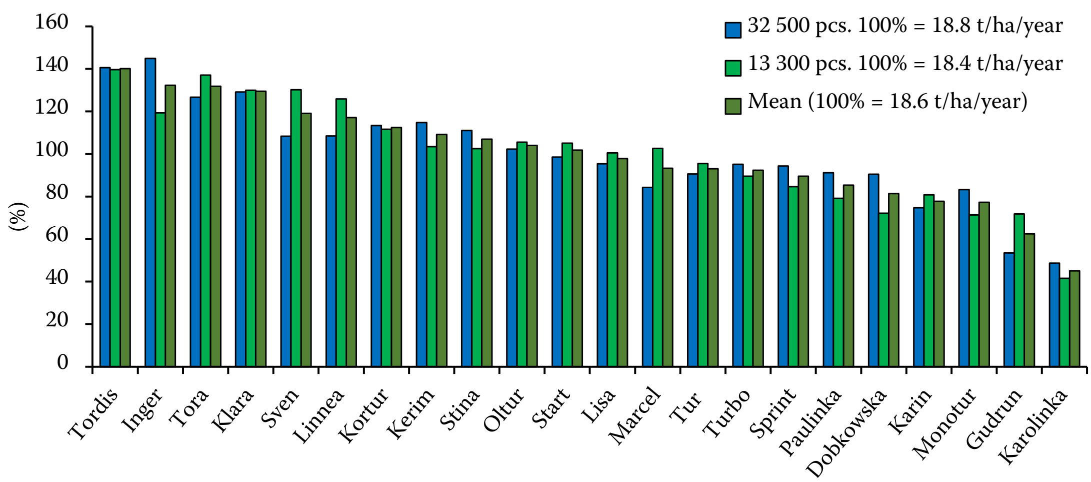

Figure 4. Estimated yield of dry matter of one-year vegetation in relation to the mean yield for a specific level

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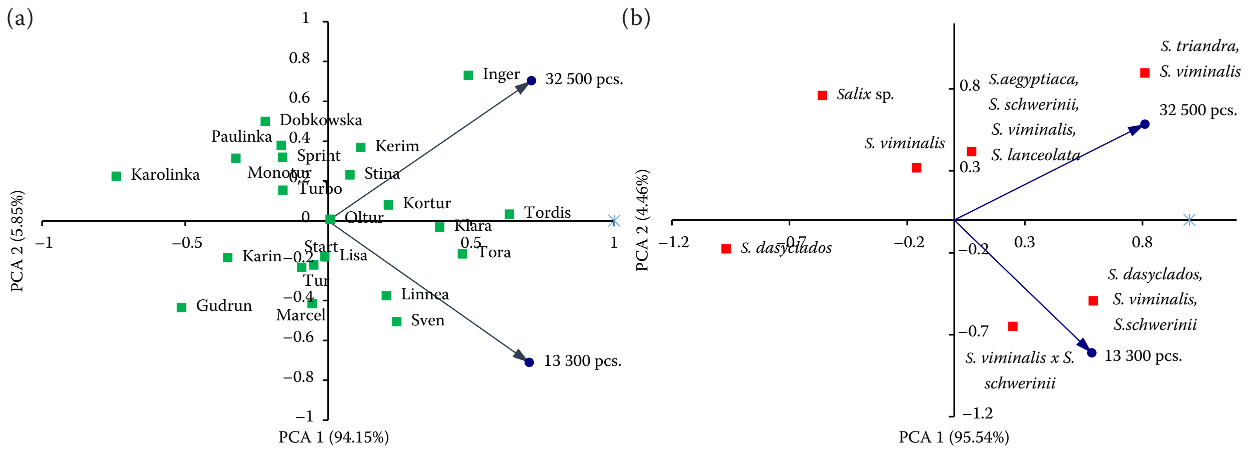

Figure 5. Vector representation of plant densities and (a) genotypes and (b) taxons in the system of principal components in consideration of dry matter yield

to the authors, *S. viminalis* is able to maintain a high stem population over time better than *S.* × *dasyclados*, due to its morphology and efficiency of the resource use. The two cultivars are morphologically different, *S. viminalis* being a taller, more erect clone in comparison to the shorter *S.* × *dasyclados* with its more lateral growth pattern. In the study of Labreque and Teoderescu (2001), who also used a 4-year cycle of harvest, the best yielding willows were *S. miyabeana*, *S. sachalinensis* and *S. ericephala*, slightly weaker were *S. dasyclados* genotypes and the lowest *S. viminalis*. According to these authors, the latter genotype under the conditions of the study was sensitive to infection with diseases and it was frequently damaged by pests. Volk et al. (2011), evaluating a trial of 32 willow clones, showed a 33.3% higher biomass yield of new clones compared to old genotypes. This increase can be partly attributed to the improved genotypes, site factors and crop management. Nissim et al. (2018) believe that the majority of commercial willow cultivars can be grown in short rotation coppice and achieve high biomass yields in most pedoclimatic conditions.

Biomass moisture during harvest. The water content in plant tissues at harvest was on average 52.3%. A significant influence of the frequency of harvest and cultivar on the water content in willow stems was found. The lowest water content was found in chips collected in a two-year cycle in the sixth year after planting. The water content in the willow stems decreased because the harvest cycle increased from one to two years. Willow stems collected in the one-year cycle had the highest (53.7%) water content (Figure 3). In the stems harvested in a two-year cycle, in the third and in the sixth year after planting the water content was 52.4% and 50.8%, respectively. A similar relationship was found by Szczukowski et al. (2002, 2005), who found that wood from the annual harvesting cycle contained 52.68% water, while in the two and three-year cycles the respective values were 49.62% and 46.05%. In the study of Wilkinson et al. (2007), the water content in one-year and two-year old stems of *S. viminalis* remained in a narrow range between 51.9% to 53.6%, while for three and four-year old stems, it was from 47.4% to 48.3%. In this field, *S. triandra* genotype differed; a high moisture difference between the first and second year of vegetation was found (54.5% and 47.9%, respectively). In the discussed studies, planting density had no significant effect on the water content in the willow stems. Also Stolarski et al. (2011) did not show significant differences between the planting densities, and the moisture content ranged from 47.5% to 52.0%. Achinelli et al. (2018) found a trend to higher moisture content with a lower planting density. Many studies have shown that the water content in willow stems depends on the genotype (Szczukowski et al. 2005, Stolarski et al. 2011, Achinelli et al. 2018). Moreover, in the present research, a significant variation of this parameter between willow cultivars was observed. Irrespective of the harvesting cycle, the lowest water content of the compared cultivars (below 50%), was recorded in Sprint, Gudrun and Karim cultivars, while the largest (over 54%) in Monotur, Oltur, Marcel, Tora and Linnea cultivars. The latter cultivars showed a similar reaction in both one-year and two-year harvesting cycles (Figure 2).

Biomass calorific value and energy efficiency. The gross calorific value of 1 t of willow biomass

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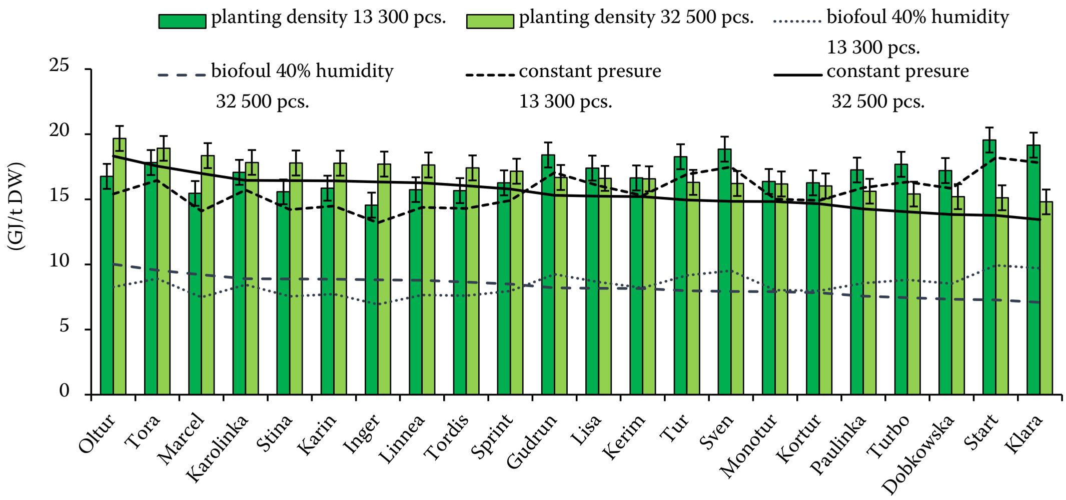

Figure 6. Gross calorimetric value (bars) and net calorimetric value (lines) of willow shoots of depending on the cultivar and plant density. DW – dry weight

ranged from 15.2–20.1 GJ/t DW (dry weight). The majority of cultivars were characterized by a higher concentration of energy with more dense planting, as compared to lower plant density. The cvs. Oltur, Tora, Marcel, Karolinka, Stina, Karin, Inger, Linnea, Tordis and Sprint exhibited considerably higher calorific value at high planting density, while a reverse relationship was determined for the remaining cultivars, in particular of cvs. Klara, Start, Tur, Sven, Gudrun and Turbo, Dobkowska and Paulinka (Figure 6).

Net calorific value at constant pressure was lower by about 8% and ranged from 13.2–18.3 GJ/t DW. The net calorific value at 40% humidity was approximately 50% lower than the gross calorific value and it ranged from 6.94–10.01 GJ/t. The presented value is similar to those obtained by other authors (Smaliukas et al. 2008, Stolarski et al. 2013, Weger et al. 2016). Cvs. Oltur, Marcel, Stina and Inger showed significantly higher calorific value with dense planting, whereas the reverse relation was found in other cultivars, in particular cvs. Klara, Start, Tur, Sven, Turbo and Dobkowska. Irrespective of the planting density, the highest calorific value of biomass was noted in Tora and Oltur cultivars, which at the same time, belonged to a group of cultivars with the highest wood moisture content. A different relationship was found in cultivars with the lowest calorific value of biomass (Dobkowska and Inger), which was characterized by relatively low wood moisture content.

Energy value of the obtained biomass yield from the tested cultivars, depending on the planting density, was determined on the basis of the calorific value

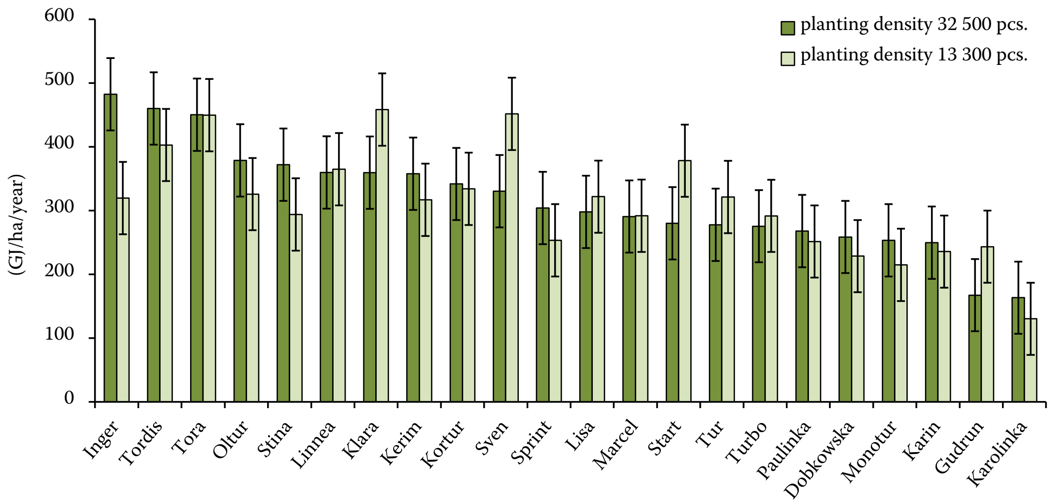

Figure 7. Energetic value of biomass of willow cultivars depending on the plant density (vertical bars indicate standard error)

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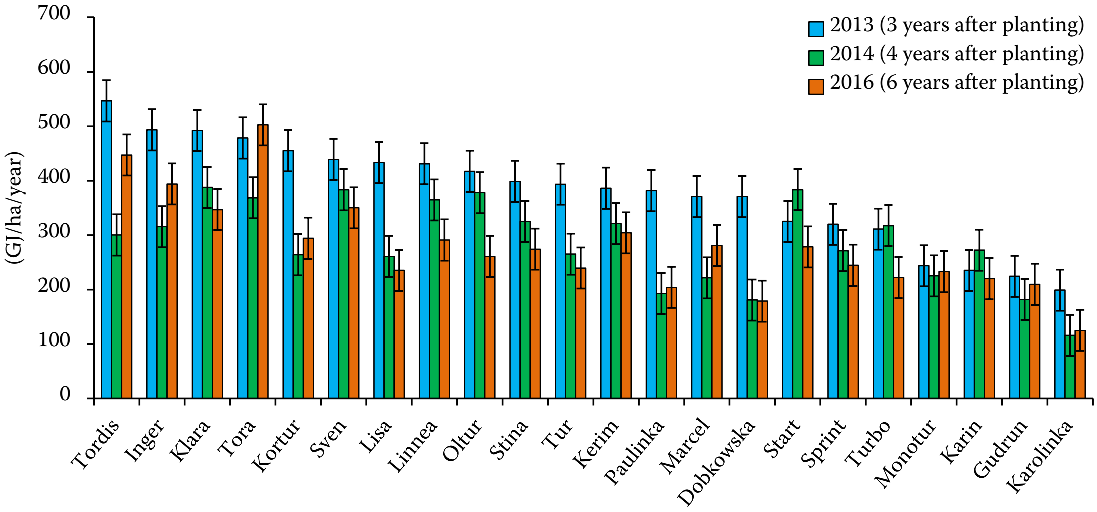

Figure 8. Energetic value of biomass of willow cultivars as depended on the years - harvest frequaency (vertical bars indicate standard error)

and dry matter yield of stems on the annual basis. The highest energy value was recorded in the Inger cultivar with high planting density, while the cv. Tordis and, in particular, cv. Tora, were characterized by an equally high energy value irrespective of the planting density. These genotypes particularly worth recommendation, as with a low effort incurred for plantation establishment they can produce a large amount of energy. Furthermore, the genotype-environment interaction is particularly expressed by the high energy efficiency of the Klara, Sven and Start cultivars with low planting density. A similar reaction was exhibited by the Gudrun cultivar, yet at a considerably lower energy efficiency level. Of these four cultivars, Klara and Sven may be recommended (Figure 7).

The value of the plantation energy efficiency depends on the cultivar and years – the harvest frequency of is shown in Figure 8. Most of the compared cultivars were characterized by a significant diversity of energy efficiency depending on the harvest frequency. In general, greater energy efficiency (329.3 GJ/ha/year) was recorded in willow cultivars collected in a two-year cycle than in the one-year cycle (286.4 GJ/ha/year). It should be pointed out that greater energy efficiency was observed in the two-year cycle collected in the third year after planting (379.5 GJ/ha/year) than in the two-year cycle harvested in the sixth year after planting (279.15 GJ/ha/year). In the one-year harvest cycle, higher energy efficiency was observed at Start and Karin cultivars when compared to the two-year cycles. Turbo, Monotur and Gudrun cultivars did not show a significant influence of the harvest frequency. Among the tested cultivars, the greatest energy efficiency in the two-year harvesting cycle, both in the third and sixth year after planting, was recorded in the cvs. Tordis, Inger and Tora. It should be noted that in the two-year harvest cycle, the Tora cultivar – in contrast to other cultivars – did not show a significant decrease in energy efficiency in the sixth year after planting compared to the harvest in the third year after planting. This suggests a desirable reaction due to the yielding stability. Cvs. Klara, Linnea, Oltur and Stina were characterized by the higher energy efficiency in the one-year harvesting cycle in comparison to the two-year harvesting cycle conducted in the sixth year after planting. Cvs. Kortur, Sven, Lisa, Tur, Kerim, Paulinka and Dobkowska did not show significant variation of these characteristics.

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