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Quantifying the peak yields of four cellulosic bioenergy crops in the East-Central Poland

Określenie szczytowych plonów czterech celulozowych roślin energetycznych we wschodniej części centralnej Polski

Summary. Through the six successive years (2010–2015), from the 5th to the 10th year of cultivation, research was carried out on yielding and species characteristics of 4 perennial vegetatively propagated energy crops. These were: 2 species of *Miscanthus*, *Sida hermaphrodita*, and 2 *Salix viminalis* clones (1047 and 1054), cultivated side-by-side. The height and shoot number, yield and biomass moisture were evaluated. The highest shoot density of *Miscanthus sacchariflorus* was found, while the largest yield of *Miscanthus* × *giganteus*. *Salix viminalis* and *Miscanthus* × *giganteus* biomass was characterized by the highest content of accumulated moisture (on average 50%). The *Sida hermaphrodita* plants were appeared as the tallest ones on the six-year average. It is worth mentioning, we have concluded that yield of *Miscanthus*, and *Sida* is high and stable in the long-term study. However, in the average yields of these 2 species (*Miscanthus* × *giganteus* and *Sida hermaphrodita*) no statistically significant differences were found. Results can strengthen the improved species diversity in perennial energy crops cultivation.

Key words: lignocellulosic species, *Miscanthus*, *Sida hermaphrodita*, *Salix viminalis*, yields

INTRODUCTION

The progressive substitution of fossil energy sources by the renewables plays a significant role in reducing of carbon dioxide emissions to the atmosphere, and supports clean environment. One of the most important renewable 3G (third generation) sources is non-edible plant biomass (bio-energy feedstocks) originating from field-crops, mainly of lignocellulosic perennial species [Lewandowski et al. 2000, Christian et al. 2008, Borkowska and Molas 2012, 2013]. In planning the production of plant biomass for energy purposes, the experience and knowledge enabling the estimation of predictable yield over a longer period of time are helpful.

Yielding of perennial species dry matter (DM) varies in subsequent years of cultivation; however, those species have the same development life-cycle. In the establishing year for all of them, above-ground mass is marginally low [Borkowska and Molas 2013], but under-ground biomass may be exceptionally large. The development cycle of crop--vitality is known; first few-year period to achieving of a fully yielding, next several years of high efficiency, and as expected gradually reduce of the yield [Christian et al. 2008]. The *Miscanthus* × *giganteus* (further as MG in the manuscript) is mostly recognized as high-yielding species. Dry mass (DM) yield often exceeds 25 t ha^{-1} in Southern Europe, under irrigation [Lewandowski et al. 2000]. However, the yields of this species range very widely, from 4 to 22 t DM ha^{-1} in Central Germany [Lewandowski et al. 2000]. Harvested biomass of the MG and *Miscanthus sacchariflorus* [Kowalczyk-Juśko and Kościk 2004] (Amur silvergrass) further as MS, like the other grass species [Clifton-Brown et al. 2001, Jeżowski 2008, Maletta et al. 2012, Payne et al. 2017], consists of a significant amount of leaves [Borkowska and Molas 2013], which are a troublesome crop residues [Adler et al. 2006, Amougou et al. 2012]. Lower biomass yields than of MG, are obtained from *Sida hermaphrodita* further as SH, however, it reached more than 22 t DM ha^{-1} [Borkowska and Molas 2012] and 25 t DM ha^{-1} [Jablonowski et al. 2017]. A direct comparison of the yields of these two species gave four-year average yields: MG 16.6 t DM ha^{-1} and 13.0 t DM ha^{-1} for SH [Borkowska and Molas 2013]. This species, as well as *Salix viminalis*, further as SV, regardless of the date of harvest, are devoid of leaves, thus, 100% of harvested dry biomass are shoots. The amount of SV yields may exceed 20 t DM ha^{-1} [Borkowska and Molas 2012], but more often 10–15 t DM ha^{-1} [Stolarski et al. 2005, Borkowska and Molas 2013], and less than 2.5 t DM ha^{-1} [Styszko and Fijałkowska 2016].

An important feature of biomass for energy is its range of moisture during harvesting procedures. Low content of water in the aboveground mass of SH allows granulation of its raw material immediately after harvest, during January–March [Gehren et al. 2019]. Biomass of SV, in particular, and MG requires its expensive dry-out [Borkowska and Molas 2013]. However, delaying of MG (and other grasses) harvest to the spring, resulted in natural moisture reduction and improve its quality [Jensen et al. 2017].

The biomass efficiency is modified not only by species traits, but also by all environment factors. The basic factors to be mentioned here are meteorological and soil conditions, and availability of nutrients. Differences in yielding of species grown in the same conditions result mainly from genetic traits and the influence of, among other, meteorological conditions on plants. The basic meteorological elements, which include air temperature and precipitation (can be determined using the Sielianinov' coefficient K), well stimulate or drastically limit the efficiency of plant species. Field-establishment numbers of crops may be reduced in huge by droughts, sudden climatic changes and drastic low temperatures in winter.

The objective of the experiment was the determination of plant grow-parameters of the selected species (main aim) of fast-growing crop for bio-energy. Besides, elemental analyses of traits and comparison of crop samples were conducted. Additionally, it was conducted as a first-ever field experiment with the special assumption – all the seedlings and cuttings were of the same mass. Supplementary hypothesis was to investigate the effect of this new feature- way on the assumption of research (same mass of all plant materials).

MATERIALS AND METHODS

The experiment was created as a set of random blocks in 2006, and was continued to the year 2015. It was carried out in the Felin Experimental Farm (51°14'N, 22°38'E, 215 m above sea level), of the University of Life Sciences in Lublin, Poland. The experiment included 5 combinations in 4 replications. The first-order factors were 4 species: *Miscanthus* × *giganteus*, *Miscanthus sacchariflorus*, *Sida hermaphrodita*, *Salix viminalis* – 1047 and 1054 clones. The cultivation years were the second-order factor. All species were propagated vegetatively: *Miscanthus* × *giganteus*, *Miscanthus sacchariflorus* and *Sida hermaphrodita* by root cuttings – rhizomes, *Salix viminalis* by stem cuttings. All used seedlings/cuttings had the same mass – each 25 g. The following stock of plants was used: *Miscanthus sacchariflorus* 2 pcs m^{-2} (1.0 × 0.5 m), *Miscanthus* × *giganteus* 3 pcs m^{-2} (1.0 × 0.33 m), *Sida* and *Salix* 4 pcs m^{-2} (0.75 × 0.33 m). The area of each plot for harvest was 9 m^2. Every year in spring, mineral fertilization was applied in the following quantities: nitrogen – 100 kg ha^{-1} N (as ammonium nitrate), phosphorus – 39 kg ha^{-1} P (as triple superphosphate), potassium – 75 kg ha^{-1} K (as potassium salt). Then, the soil was broken in the inter-rows with the grounding tool. The collection was carried out in the second half of November (17–22.11). Before harvest, the height of 10 shoots was measured on each plot (40 in combination). After the harvest, the mass was weighed, a sample of plant material was taken to determine the humidity (drying at 105°C according to the Norm PN-EN 14774-1:2010 for 3 h). For the verification of the numbers (density), shoots were counted per 1 m^2 of each plot. The results were analyzed statistically based on the ANOVA model. During the study period, a large variation in air temperatures and rainfalls was noted (Tab. 1). The vegetation periods 2012 and 2015 were characterized by high temperatures (three degrees above the century-average), combined with a drastic shortage of a precipitation (50% below of the century-average). Very low temperatures, the absence of snow cover occurred in winter 2011/2012.

Table 1. Average air temperature and precipitation sum for vegetation period (11.04–20.10) and year while conducting research on the background of long-term averages (1951–2010), according to the Meteorological Station in Felin, Poland

Weather factors	Year						
	2010	2011	2012	2013	2014	2015	1951–2010
Temperature (°C)	15.4	15.6	16.4	15.8	15.5	16.2	13.2
Precipitation (mm)	594.6	419.3	309.6	456.5	524.8	339.4	440.1

The Sielianinov's hydrothermal coefficient (K) was calculated by dividing 10× the total rainfall (P) by the total mean circadian (t) temperature (quotient of the total rainfall and 0.1 of the sum of average temperatures) for the given period (Tab. 2).

$$K = \frac{P}{0,1\Sigma t}$$

K – values less than 1.3, less than 0.5, and less than 0.25 represent a shortage of precipitation, drought, and disastrous drought, respectively. The optimum growing season (April to October) was determined based on the mean value of hydrothermal coefficients over the last 50 years (*K* = 1.56).

Table 2. Values of Sielianinov' (K) hydrothermal coefficients during vegetation (11.04.–20.10) periods, over 2010–2015, and multi-annual averages (1951–2010)

Month	Year						
	2010	2011	2012	2013	2014	2015	1951–2010
April	0.54	1.00	0.83	1.09	1.89	1.31	1.76
May	3.50	0.95	1.20	2.15	4.54	2.72	1.51
June	1.21	1.22	1.21	1.91	1.60	0.22	1.35
July	1.51	3.32	0.79	2.11	1.47	0.68	1.47
August	2.22	1.12	0.63	0.30	1.81	0.11	1.33
September	3.18	0.12	0.76	1.82	0.60	2.43	1.42
October	0.81	1.51	1.50	0,26	0.04	2.87	1.70
Mean	2.01	1.39	0.98	1.50	1.75	1.09	1.56

K ≤ 0.4 – exceptionally dry; 0.4 – ≤0.7 – extremely dry; 0.7 – ≤1.0 – dry; 1.0 – ≤1.3 – quite dry; 1.3 – ≤1.6 – optimum; 1.6 – ≤2.0 – quite moist; 2.0 – ≤2.5 – moist; 2.5 – ≤3.0 – very moist; >3.0 – extremely wet [Skowera and Puła 2004, Skowera 2014]

RESULTS

The species here examined, differed not only in the size of biomass yields, but also in the number of shoots and their height. The results presented in Table 3 indicate the highest shoots of *Sida hermaphrodita* (SH), and the lowest of sugar-miscanthus (MS). There were no significant differences between the height of MS shoots and willow' clone 1054 (SV). Within six years of research, the most beneficial conditions for shoot growth occurred in 2011 (the 6th crop year), and the least favorable in 2012 (the 7th year). The values of this feature were 295 and 188 cm, respectively. In the 10th year of cultivation (2015) the height of SH shoots exceeded 335 cm, not much lower shoots of this species were found in the 5th and 6th year of cultivation. From the all tested species, MS was stood out with the lowest shoots' height in all years of study, except 10th year of cultivation (Tab. 3).

Average values for species heights and all years were statistically significantly different from each other. The exception is willow between clones, in 2010 and 2012. Over the years of study, the smallest mean number of shoots – less than 30 pieces (25–28) on one square meter – was found in both willow clones. In the 9th year of cultivation, regardless of species, the mean number of shoots per one m^2 exceeded 100 (107.9); while in the 5th year of cultivation (2010), just over 70 (73.7). SH, and SV-1047 clone, in the 5th and 9th year of cultivation, were characterized by a similar number of shoots (33.7–41.9 pcs m^{-2}). In 2015 (the tenth year of cultivation), hot and dry weather condition induced the smallest shoot density (10–15 pieces) by SV-clones. Plants of MS species produced the significantly more shoots; their density per one m^2 was almost 270 pieces, many times more than other species (Tab. 4). Average values for shoots' density were statistically significantly different from each other. The exception is willow between clones.

Table 3. Height of shoots (cm) of 4 species in the period from 5th to 10th year of cultivation

Species	Year of cultivation						Mean
	5th (2010)	6th (2011)	7th (2012)	8th (2013)	9th (2014)	10th (2015)	
MS	157.3^{bc}	231.5^{ef}	157.0^{bc}	166.0^{cd}	174.5^{cd}	158.8^{bc}	174.3^{A}
MG	304.5^{hij}	310.5^{hij}	193.5^{d}	181.3^{cd}	259.3^{fg}	231.3^{ef}	246.7^{C}
SH	330.3^{ij}	336.3^{ij}	211.8^{de}	258.3^{fg}	302.3^{hij}	338.5^{j}	296.2^{D}
SV-c. 1047	285.0^{gh}	301.5^{hij}	189.0^{cd}	237.3^{ef}	297.5^{hi}	93.5^{a}	234.0^{B}
SV-c. 1054	290.5^{gh}	297.8^{hi}	190.5^{cd}	247.5^{f}	282.5^{gh}	123.5^{ab}	238.7^{BC}
Mean	273.5$^{\mathrm{C}}$	295.5$^{\mathrm{D}}$	188.4$^{\mathrm{A}}$	218.1$^{\mathrm{B}}$	263.3$^{\mathrm{C}}$	189.1$^{\mathrm{A}}$	238.0

Designation with the same letters determines values not significantly different at $P = 0.05$
A, B, ... – for year, *A, B, ...* – for species, a, b, ... – for year × species interaction

Table 4. Density of shoots (pcs m^{-2}) of four species within the 5th to the 10th year of cultivation

Species	Year of cultivation						Mean
	5th (2010)	6th (2011)	7th (2012)	8th (2013)	9th (2014)	10th (2015)	
MS	175.9^{i}	281.5^{k}	254.5^{j}	279.8^{k}	318.2^{l}	307.0^{l}	269.5^{D}
MG	80.2^{ef}	108.0^{g}	108.5^{g}	91.0^{f}	125.1^{h}	70.6^{e}	97.2^{C}
SH	41.9^{cd}	45.8^{d}	32.7^{bd}	30.1^{bc}	33.7^{bcd}	32.1^{bcd}	36.0^{B}
SV-c. 1047	39.4^{cd}	29.8^{bc}	21.1^{ab}	29.7^{bc}	33.7^{bcd}	15.0^{a}	28.1^{A}
SV-c. 1054	31.3^{bc}	32.7^{bcd}	25.1^{ab}	22.8^{ab}	28.9^{bc}	10.1^{a}	25.2^{A}
Mean	73.7$^{\mathrm{A}}$	99.6$^{\mathrm{C}}$	88.4$^{\mathrm{B}}$	90.7$^{\mathrm{B}}$	107.9$^{\mathrm{D}}$	87.0$^{\mathrm{B}}$	91.2

Explanations as in Table 3

Moisture of biomass during harvesting time is important in bio-energy use. In the case of species with straw or semi-wooden stems, the water content largely depends on the date of harvesting. In the autumn, biomass is more humid than harvested in winter, except trees, and shrub's willow alike. For trees and shrubs (short rotation forestry and coppicing trees), the date of harvesting does not matter; those species year-around have a high moisture. Willow's shoots have most moisture off all studied species (47.9–

52.3%). Surprisingly, the moisture of MG (49.3–50.8%) over the study was similar to the moisture of both SV-willow clones (Tab. 5). During the six-year study period, the lowest water content was recorded in biomass of SH (11.1–28.6%) and MS (14.1–26.6%). In the literature, the role of bio-energy crop-shoot structure for the process of natural drying out of biomass (by senescence) is rarely emphasized. The great and significant difference in moisture level in unharmed shoots, among species, mainly results from their structure. Shoots of SH in whole length have a pith, which with time transforms into a long tube, without locking (divisive) nodes. Its semi-woody structure with a tube inside, facilitates of natural dry-out of shoots. In the case of MS, its grass shoots (are straw-alike), have long internodes and little locking nodes. It's that helps by dry-up. MG is also a grass species as the MS; however, its shoots are thick. Internodes are short, stems to have many divisive nodes – that makes it difficult to get rid of moisture. Shoots of SV clones have a tree-structure. High moisture level varies a little in the season, and it keeps the tree shoots alive.

Table 5. Moisture (%) of biomass during the harvest in November, in the period from 5th to 10th year of cultivation

MS	MG	SH	SV-c. 1047	SV-c. 1054
14.1–26.6	49.3–50.8	11.1–28.6	48.8–52.3	47.9–51.8

Over years of study, the biomass yields of the tested species differed significantly. Yields of MG (18 t DM ha^{-1}) were almost twice as high as SV-clones yields (Tab. 6). The average yield of MS from six years was 1.58 t DM ha^{-1} lower, and of SH 2.47 t DM ha^{-1} lesser than of MG. It was found, that there are no statistically significant differences of mean yields among three species MG-MS-SH. Not only in the 7th (2012) year of cultivation, but also in 10th year (2015), the yields were the lowest. In the localization of research (East Poland), in 2012 and 2015, the growing seasons were characterized by unheard earlier of so high temperatures (35–40°C) combined with a huge precipitation shortage, with less than 300 mm of rainfall. In 2012, SV-clone's yields were declined to the 4.9 and to 6.4 t DM ha^{-1}, and in 2015, fell to 1.4 t DM ha^{-1}. Notabene, all of *Salix* plants observed in the recent experiments have been completely withered (dead) in 2016. In the 6th year of cultivation (2011), the yield of MG was close to 30 t DM ha^{-1}, and the MS and SH have exceeded 20 t DM ha^{-1}. The yields of both SV clone's slightly exceeded 15 t DM ha^{-1}; a similar yield level was recorded in the 8th and 9th years of cultivation of MG and SH.

The calculated correlation coefficients indicate a high dependence of all species' yield on the shoot height. The correlation between yield and plant-density is high-significant by *Sida* and *Salix*. Correlation between high × density for yield is high-significant by *Salix* (Tab. 7).

Table 6. Yields of dry matter (t DM ha^{-1}) of four species from the 5th to 10th year of cultivation

Species	Year of cultivation						Mean
	5th (2010)	6th (2011)	7th (2012)	8th (2013)	9th (2014)	10th (2015)	
MS	14.2^{o}	20.2^{l}	12.2^{efg}	16.9^{ijk}	17.6^{k}	17.5^{k}	16.44^{B}
MG	26.3^{l}	29.6^{m}	10.2^{cd}	12.8^{efg}	16.8^{jk}	12.5^{efg}	18.02^{B}
SH	21.2^{l}	21.7^{l}	10.3^{cd}	13.4^{fi}	13.9^{gi}	13.4^{fi}	15.65^{B}
SV-c.1047	12.3^{efg}	15.4^{hij}	4.9^{b}	10.7^{de}	11.4^{cdf}	1.4^{a}	9.36^{A}
SV-c.1054	13.2^{fgi}	15.1^{hij}	6.4^{b}	9.9^{cd}	9.6^{cd}	1.4^{a}	9.26^{A}
Mean	17.44^{D}	20.39^{E}	8.82^{A}	12.74^{B}	13.84^{C}	9.25^{A}	13.75

Explanations as in Table 3

Table 7. The calculated correlation coefficients for yields, hight and density of 4 crops

Given trait	MS	MG	SH	SV-1054	SV-1054
Hight	0.700^{xxx}	0.853^{xxx}	0.695^{xxx}	0.938^{xxx}	0.934^{xxx}
Plant-density	0.542^{xx}	0.540^{xx}	0.848^{xxx}	0.813^{xxx}	0.878^{xxx}
High × density	0.233	0.360	0.516^{xx}	0.878^{xxx}	0.888^{xxx}

^{xx} significant by $P < 0.01$, ^{xxx} significant by $P < 0.001$

Table 8. Comparison of some alternative perennial cropping systems, six-year cumulative biomass DM yields (t ha^{-1})

Specification	Borkowska and Molas [2013]	Data from recent manuscript	Borkowska and Molas [2013] and recent manuscript	Borkowska and Molas [2013]/ Sanford et al. [2016]		Sanford et al. [2016]
Years of cultivation	1st–4th	5th–6th	1st–6th	1st–6th		1st–6th
Yield type	yield	yield	cumulative yield	plant rate (thousands ha^{-1})		cumulative yield
Miscanhus MG	65.9	55.9	**121.8**	30	17	**65.2**
Miscanthus MS	24.7	34.4	59.1	20	–	–
Sida H	52.2	42.9	**95.1**	40	–	–
Switch Grass	–	–	–	–	–	**25–32**
Hybrid Poplar	–	–	–	–	2.8	**55.4**
Salix 1047	40.7	27.7	68.4	40	–	–
Salix 1054	35.4	28.3	63.7	40	–	–

Miscanthus MG (*Miscanthus × giganteus* Greef & Deuter ex Hodkinson & Renvoize), Miscanthus MS (*Miscanthus sacchariflorus* (Maxim.) Hack.), Sida H (*Sida hermaphrodita* L. Rusby), Salix 1047 and 1054 (*Salix viminalis* L. clones)

Considering that the yields of perennial crops have constant upward trend (caused by its life-cycle), yield reduction results only from extremely poor conditions (no precipitation) during the growing season. It was found, that the volume of given species yields in the subsequent years, was less dependent on the aging of plants than on weather factors. This is particularly evident in the yield changes of *Salix* clones.

DISCUSION

Yielding depends on various elements, e.g., of the crop architecture, including plant height and density (shoot numbers). The height of plants, apart from genetic traits, is influenced by agri-ecological conditions that are often dominant. The first four year of studied species cultivation was described by Borkowska and Molas [2013]. By successive studies on yield comparison of the same species (mentioned here), under the same soil and site conditions (side-by-side), and initial mass of seedlings was for a principle identical, it allowed for found, that the main factors which caused the differentiating of the growth and development of plants were meteorological elements. In a recent study, it was found a much smaller density and height of shoots in dry years than in years with optimal hydrothermal conditions, and it was significantly different.

Species *Salix* is more sensitive to water shortages than *Miscanthus* and *Sida*, it because, *Salix* has not a storage-roots system as some herbaceous crop have. The height of the shoots SV clones 1054 and 1047, harvested each year in favorable humidity conditions was by other authors find as close to 3 m [Stolarski et al. 2005, Borkowska and Molas 2012]. However, in 2011, shoots reached 3 m in this research too, but in the dry year 2015, the height of shoots of the same clones oscillated between 0.9 and 1.2 m, and their number decreased to a dozen or so. As a result, the yields of DM of 1047 and 1054 clones (Tab. 4) were lower than 1.5 t DM ha^{-1}, and average yields from six years did not exceed 10 t DM ha^{-1}. Willow in other studies yielded on average within four years 15–18 t DM ha^{-1} [Stolarski et al. 2005, Szczukowski et al. 2009, Borkowska and Molas 2012].

Many authors indicate an MG as a species with a very high yield-potential [Lewandowski et al. 2000 (4–25 t DM ha^{-1}), Clifton-Brown et al. 2001 (0–36.8 t DM ha^{-1}), Christian et al. 2008 (average 17.7 t DM ha^{-1}), Jeżowski 2008 (2–15 t DM ha^{-1}, Oliveira et al. 2017 (4-yr mean 17.6 t DM ha^{-1})]. Other authors recorded distinct lower yield results for SV and MG [Kopp et al. 2001, Styszko and Fijałkowska 2016, Amaducci et al. 2017, Xu et al. 2017, Dubis et al. 2019]. Furthermore, in the recent study, on average, within six years (from 5th to 10th of cultivation), the highest yields of DM were obtained from MG. In the 5th and 6th year of cultivation, the range of yields of this species reached 26–29 t DM ha^{-1}. However, in subsequent years, from the 7th to the 10th year of cultivation, yields were significantly lower, from 10 to 17 t DM ha^{-1}. It is the visible effect of drastic environment condition's change; middle temperatures to the half January 2012 (+5°C) and in next few days sudden harsh frosts (–30°C) in winter 2011/2012. And then, drought-year 2012 – none of the species studied reach yields recorded earlier. Furthermore, in the case of SH, the highest yields, 21 t DM ha^{-1}, were recorded in the 5th and 6th year of cultivation. Then, the efficiency decreased to 10–13 t DM ha^{-1}. Higher yields of SH (25 t DM ha^{-1}) were obtained by Jablonowski et al [2017] with seedlings, without fertilization. Borkowska et al. [2015] have used seeds and received mean yield level 17 t DM ha^{-1}.

The case of MS yield is very interesting. This species resistant to low temperatures [Pignon et al. 2019], unlike the other species studied, after the harsh winter of 2011/2012, in the following years yielded higher than the other studied species. The yield on average from six years exceeded 16 t DM ha^{-1}. In the initial four years of cultivation (2006–2009) described by Borkowska and Molas [2013], the average yields of MS were more than twice lower than in the 5th to 10th year of cultivation (2010–2015). Yields of MG and SH have been around 2 t DM ha^{-1} higher in the discussed six-year period, than in the first four years. Only yields of both willow clones remain at a similar level. Not without significance is the fact, that the *Sida* and *Salix* biomass harvested in late autumn (second half of November) does not contain leaves; it is in the contrast to the *Miscanthus* biomass, especially the MG. Leaf litter inflates *Miscanthus*' yields, and at the same time reduces the energy value of its biomass [Molas et al. 2018], that is applied to all grasses species. The considerable winter hardiness and high yields of MS was indicated by Arnoult and Brancourt-Hulmel [2015]. It is worth paying attention how the difference in yields may indicate a varied rate of development of the studied species, and its resilient to the droughts and frosts. Shrub-willow (SV) biomass regardless of the date of harvest, approximately consists of 50% water [Stolarski et al. 2005, Stolarski et al. 2019]. Similar SV moisture was found in the presented studies (48–52%). High content of water is high-associated with low calorific value, higher transport costs (water mass) and energy-intensive dry-up, or several months of seasoning. In the freshly harvested biomass of MG, a similar amount of water is contained as in willows (Tab. 5). Low moisture of both, MS and SH, is noted as very sustainable and environment-friendly; species dry-up by senescence on the fields. Such biomass can be pressed for pellets directly after harvest without drying [von Gehren et al. 2019].

It may be worth using the opportunity and giving a summary of mean yield results from two separate studies (2006–2009) and (2010–2015), but with the same set of four crop species, from the same plots. The highest average yield in 10 years of research has been achieved by MG (17.25 t DM ha^{-1} year^{-1}), then in succession SH (14.34 t DM ha^{-1} year^{-1}), MS (11.31 t DM ha^{-1} year^{-1}) and the lowest by SV-1047 (9.7 t DM ha^{-1} year^{-1}) and SV-1054 (9.05 t DM ha^{-1} year^{-1}). Lowest yields by *Salix*, they are in contrast to the results achieved by other authors [Stolarski et al. 2019]. *Salix* (and *Populus* sp.), *Miscanthus* (and *Panicum virgatum*) are those species which authors consider most, as biomass crops for bio-energy. *Sida hermaphrodita*, native to USA [Rickett 1963, Spooner et al. 1985, Kujawski et al. 1997], and semi-domesticated in Poland [Borkowska and Molas 2012, 2013], by many authors has been recognized as a unique species against other on this background [Jablonowski et al. 2017, Molas et al. 2018, Gehren et al. 2019]. Other authors concluded that *Sida* is prospective species for the biorefineries [Damm et al. 2017a, b]. Although for many researchers, *Sida* species is still unknown, despite that *Sida* is native to USA and Canada. Sanford et al. [2016] studied more than 20 native US Species and corn, miscanthus, poplar, neither *Sida.* According to the results of the six-year cumulative DM yields in Southwest Michigan reported by Sanford et al. [2016], it can be shown *Sida* yields on this background, by the comparative summary of the results in North Central USA (ARL, 43°17'N, 89°22'W, 315 m a.s.l; KBS, 42°23'N, 85°22'W, 288 m a.s.l) and East Central Poland (51°14'N, 22°38'E, 215 m a.s.l). Six-years cumulative yield of *Sida* is almost 50% higher than those of *Miscanthus* reported by Sanford et al. [2016]. Recent study show, and research of other authors allow to consider to count also species *Sida hermaphrodita* as a promising and high valuable bio-energy feedstock.

CONCLUSIONS

The recent study, focused on four lignocellulosic bio-energy species, showed that the on an average, from 6 years of cultivation, the highest biomass yields were obtained from the cultivation of *Miscanthus* × *giganteus* (MG), the lowest of both *Salix viminalis* clones (SV). In the years with a drastic shortage of precipitation (2012 and 2015 – the 7th and 10th year of cultivation), the meanest average biomass yields of all species studied were found, associated with the lowest height and shoot density. The density of *Miscanthus sacchariflorus* (MS) shoots was several times higher than other species; however, it did not cause with the highest yield, due to the straw nature of the shoots. The least moisture content was recorded in biomass of *Sida hermaphrodita* (SH) and *Miscanthus sacchariflorus* (MS).

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Streszczenie. Badania dotyczące plonowania i charakterystyki 4 gatunków wieloletnich roślin energetycznych rozmnażanych wegetatywnie przeprowadzono przez kolejnych 6 lat (2010–2015), od 5. do 10. roku uprawy. Były to 2 gatunki miskanta, ślazowiec pensylwański i dwa klony wierzby wiciowej (1047 i 1054) uprawiane obok siebie. Oceniano wysokość i liczbę pędów oraz plon i wilgotność biomasy. Największą gęstość pędów stwierdzono u miskanta cukrowego, natomiast największy plon osiągnął miskant olbrzymi. Biomasa wierzby i miskanta olbrzymiego charakteryzowała się największą wilgotnością (średnio 50%). Średnio dla 6 lat badań najwyższe pędy miał ślazowiec pensylwański. Warto podkreślić, że w długookresowych badaniach wydajność miskanta olbrzymiego i ślazowca pensylwańskiego była wysoka i stabilna. Ponadto nie stwierdzono istotnych różnic w średnich plonach tych 2 gatunków (*Miscanthus* × *giganteus* i *Sida hermaphrodita*). Uzyskane rezultaty mogą sprzyjać zwiększeniu różnorodności gatunkowej w uprawach wieloletnich roślin energetycznych.

Słowa kluczowe: gatunki ligninocelulozowe, miskant, ślazowiec pensylwański, wierzba, plony

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