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Production and allocation of biomass and radiation use efficiency in four clones of *Salix viminalis* L.

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Abstract. In this paper are presented results of experiments with willow clones in IUNG-PIB in Poland at the Osiny Experimental Station and at the Grabów Experimental Station, as well as clonal variability of basal biometric parameters of willow forms selected for cultivation. Dry matter allocation and its sun radiation efficiency were discussed. Number of stems per stool, shoot diameter, shoot height and leaf area index were studied. The highest yields were recorded in 2004 and the lowest in 2006. Significantly higher number of stems per stool was found for clone 1054 at Osiny. The greatest share of shoots in the biomass was found in clones 1023 and 1054. Solar radiation use efficiency by the willow was comparable to the values reported in the literature.

key words: willow, *Salix viminalis*, clones, production of biomass, dry matter allocation, radiation use efficiency

INTRODUCTION

Due to growing renewable energy requirements by power and heat plants in Poland, there are still increasing biofuel shortages. The EU aims at increasing the share of renewable energy of the total primary energy consumption from 6.4% in 2004 to 20% in 2020 whereby bioenergy is expected to play an important role (Directive..., 2009). Owing to this issue and because of competition from food crops for land, short rotation-based intensive management of willow has gained much interest. Main research objectives centre on maximizing annual woody biomass yield per hectar as a result of appropriate levels of fertilization and proper methods of chemical protection. An important issue is the assessment of biomass of energetic plants under management conditions economically effective in Poland. Also, dry matter allocation is worth particular attention. The success of the biomass production depends, in part, on the efficient coupling of genetic and environmental factors to generate efficient production systems. In this paper are presented results of experiments with willow clones in IUNG-PIB in Poland, as well as clonal variability of basal biometric parameters of willow forms selected for cultivation. Dry matter allocation and its sun radiation efficiency were also discussed.

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MATERIAL AND METHODS

The plantations were established at the Osiny Experimental Station in the Lubelskie voivodship (51˚42'N, 22˚04'E, 153 m above sea level) and at the Grabów Experimental Station in the Mazowieckie voivodship (51˚21'N, 21˚40'E, 167 m above sea level) – both experiments were started in the spring of 2003. The soil at the site at Osiny is sandy clay loam (pH_{KCl} 4,42), while soil at the site at Grabów is loamy sand (pH_{KCl} 4,61). Grabów Exp. Sta. area is situated in the Mazowiecka Lowland. Mean monthly temperature in the period from 1962 to 2006 was 7,8ºC. Annual precipitation sum is between 426–888 mm, with 451 mm in the growing period (233–736 mm) (Fig. 1). Osiny Exp. Sta. area is assigned to the Lubelska Upland. The mean monthly temperature is 7,9ºC (1951–2006), precipitation sum is between 330 and 953 mm in year and 217–801 in the growing period (at the average 414 mm) (Fig. 1). Actual total incoming active radiation at Osiny and Grabów is shown in Figure 2. The experiment was conducted under conditions of potential strong self-thinning – planting density was about 40 000 cuttings ha^{-1}.

Pre-planting preparation included a glyphosate (Roundup, 5,0 l ha^{-1}) herbicide treatment. Levels of mineral fertilization in plantations are shown in Table 1. At both sites the plantation was planted in four blocks in a random block scheme. All plots were planted using 25 cm hardwood cuttings, spaced 0,8 m between and 0,31 within rows, giving a final planting density of about 40 000 plants ha^{-1}.

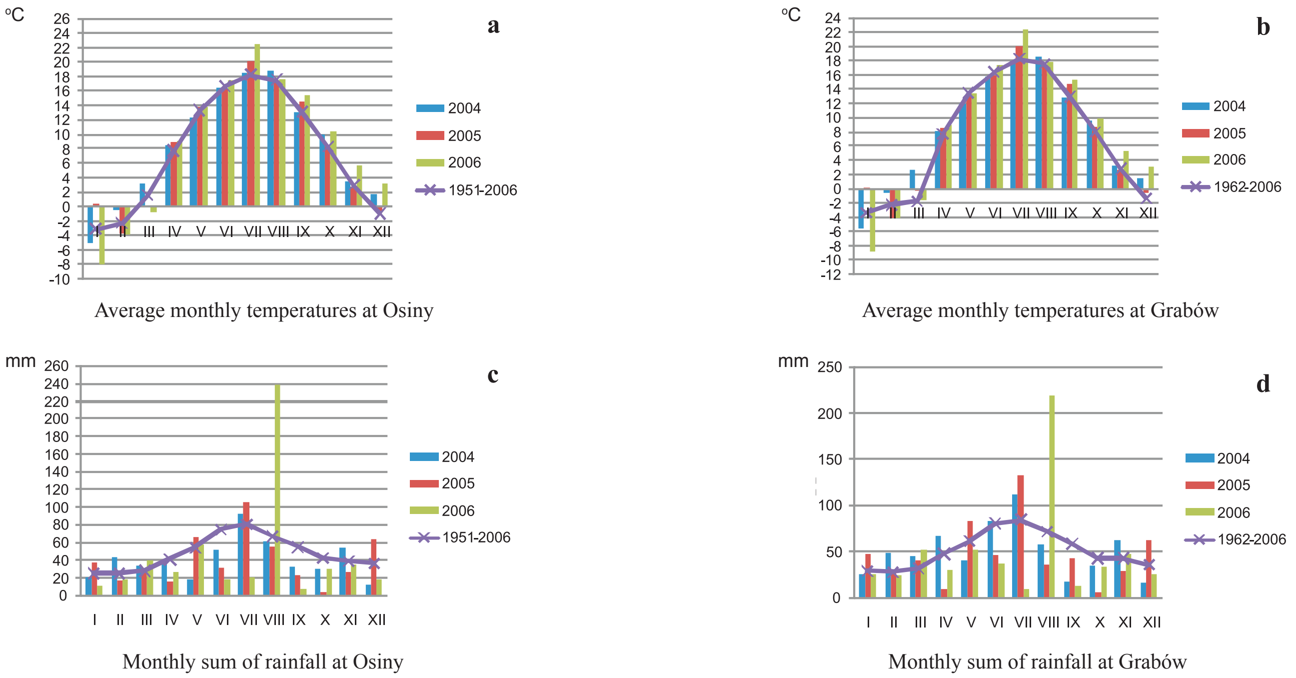

Fig. 1. Monthly distribution of temperature and rainfall during experiment.

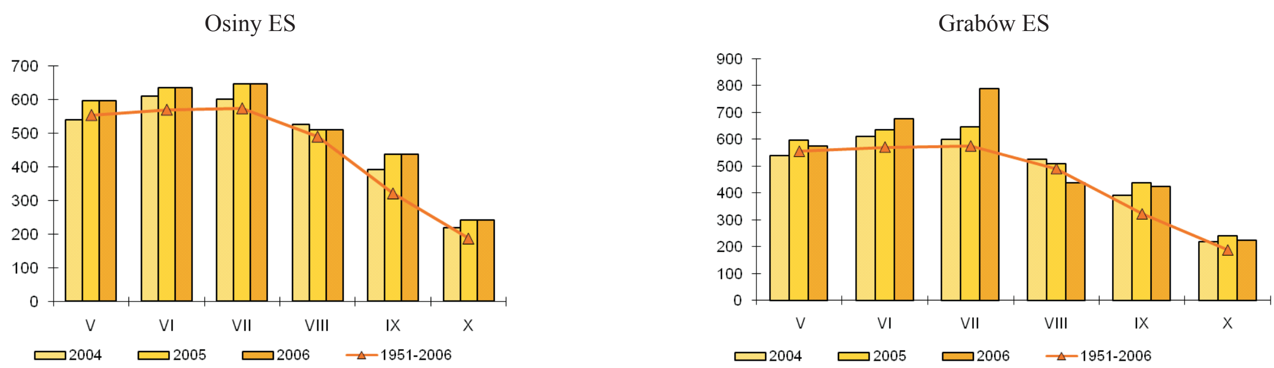

Fig. 2. Monthly distribution of total incoming active radiation (mm) during the growing period in the years 2004–2006 (according to Borzęcka-Walker, 2008).

In the field trial four willow clones of *Salix viminalis* (1023, 1047, 1052, 1054) obtained from the University of Warmia and Mazury in Olsztyn were tested. The study was conducted during the second, third and fourth annual rotation cycle in 2004, 2005 and 2006, respectively. Mechanical weeding was carried out during all four growing seasons. Herbicides were applied in 2005 and 2006 (Azotop 50 WP – 1,5 kg ha^{-1}) using a spraying device with the nozzle protected by a hood to minimize impact on the trees. Pesticides against *Venturia salicyperda* (Miedzian – 3 l ha^{-1}) and *Aphrophora salicis* (Decis 0,4 l ha^{-1}) were also applied. Every year in winter (2004–2006), plants were cut back to a height of 5 cm using a chain saw to create a coppice system. Furthermore, yield per hectare for each clone was assessed by weighing the shoots together from 5,4 m^2 net plots in five replications using a field balance. Dry matter

Table 1. Scheme of fertilization in Osiny and Grabów plantations.

Year	Osiny ES N	Osiny ES P	Osiny ES K	Grabów ES N	Grabów ES P	Grabów ES K
	kg ha^{-1}					
2004	90	26	50	100	26	50
2005	75	22	62	75	22	62
2006	75	22	62	75	22	62

content was calculated using shoot sampling method described below. The trees that did not survive were replaced with new cuttings in the spring next year (mortality rate was not higher than 5%).

In each experiment year, three willow shoots in five replications per plot were harvested from different stools five times at two-week intervals starting from June. Furthermore, in July in the period of maximum LAI of each growing season, leaf samples were taken in five replications from three representative shoots of individual clones at both sites. Shoot samples were taken also just before harvest. The leaves and cut shoots were put in paper bags and immediately weighed. Dry weight was determined after drying leaves and shoots at 80^{o}C until constant weight. In each plot, the height H (±1 cm) and the diameter of living shoots of five representative plants at 15 cm above stool base D_{15} (±0,01 cm) were measured before harvest. The number of living shoots of those plants was also assessed. Leaf area index was measured every two weeks in the growing period using a surface area meter (Li-Cor 2000, Lincoln, NE, USA). Findings resulting from allometric relations between shoot D_{15} or height H and dry weight of shoots were presented in the thesis of Borek (2008). All parameters of shoots (height, diameter, quantity) and biomass measurements were subjected to the analysis of variance (ANOVA) in Statgraphics program. Tukey method was applied to assess the significance of differences at P = 0,05. Incoming solar radiation was obtained from the meteorological stations at Osiny and at Grabów (Fig. 2).

The conversion efficiency was calculated for each clone from yields (g m^{-2}) converted from the shoot weights measured during the growing season and the respective PAR values were converted from LAI coppice measurements:

$$IPAR = PAR[1-\exp(-k\ LAI)]$$

where:
k – extinction coefficient (0,6),
LAI – Leaf Area Index [$m^2_{\ leaves}\ m^{-2}_{\ ground}$]

RESULTS AND DISCUSSION

Mean number of stems per stool was 8 (Table 2). In 2004 mean number of stems was 10. Next year, number of shoots diminished by 3 on average. In 2006, there were 9 shoots per plant at Osiny and 8 at Grabów. The highest number of stems per plant was observed in 2004. A higher number of stems per stool was found for clone 1054 at Osiny. Mean shoots diameter was 9 mm. It was not significantly different between clones and years. Mean shoot height was 2.50 m in Osiny and 2.56 m in Grabów. The highest plants were found in the first year of experiment – 3.02 m in Osiny and 3.32 m in Grabów. In the next years, due to deepening drought, mean height of shoots decreased by 29% in Osiny and 39% in Grabów in 2006. Maximal leaf area index was recorded in 2004 as the lowest (5.07 in Osiny, 4.41 in Grabów) and in 2006 as the highest (5.85 in Osiny, 5.23 in Grabów). Generally, clone 1052 was characterized by the highest rate of leaf area.

Yields of aboveground biomass are presented in Table 3. Only yields of dry matter will be considered, because of their real usefulness for energetic purposes. Aboveground woody biomass production of different clones ranged from 9.4 (clone 1047, Grabów, 2005) to 17.2 t DM ha^{-1} (1052, Osiny, 2004). Assuming 5 MWh per t DM (IE, in: Borek 2008), the biomass yield is equivalent to about 47–86 MWh ha^{-1}. There were no statistically valid differences between yields in years and (except 2004 in Osiny) in experimental stations. Generally, the yield was the highest in the first year of experiment – 14.7 t DM ha^{-1} in Osiny and 13.3 t DM ha^{-1} in Grabów. The lowest yield was obtained from clone 1054. The yields were obtained at the climatic water balance amounting to -107 mm at Osiny from April to June and -121 mm at Grabów in the same period. Hence, water conditions were good for willow. Yields in 2005 were lower than those in the year before – 12.8 t DM ha^{-1} at Osiny and 10.8 t DM ha^{-1} at Grabów. A more severe drought with a water deficit from April to June of -217 at Osiny and

Table 2. Basal biometric parameters of four willow clones.

Station	Year	Number of living shoots				Diameter of shoot (15 cm above stool), [mm]				Height of shoot [m]				LAI max			
		clone															
		1023	1047	1052	1054	1023	1047	1052	1054	1023	1047	1052	1054	1023	1047	1052	1054
Osiny	2004	12	9	8	13	9	9	10	7	2.93	3.13	3.29	2.72	4.90	5.61	5.99	3.74
	2005	6	6	6	11	9	9	10	8	2.41	2.38	2.50	2.14	4.45	5.47	5.88	5.77
	2006	8	7	7	13	10	11	10	8	2.22	2.24	2.12	1.98	5.82	5.67	6.23	5.69
	average	*9*	*7*	*6*	*12*	*9*	*10*	*10*	*8*	*2.52*	*2.58*	*2.64*	*2.28*	*5.06*	*5.58*	*6.03*	*5.07*
Grabów	2004	10	8	10	12	10	9	8	9	3.58	3.29	3.12	3.30	4.04	4.76	5.01	3.84
	2005	7	6	8	7	8	8	8	8	2.28	2.10	2.08	2.34	5.27	5.26	5.69	4.64
	2006	7	6	11	8	10	9	9	9	2.27	1.89	1.90	2.06	5.33	5.67	5.03	4.89
	average	*8*	*7*	*10*	*9*	*9*	*9*	*8*	*9*	*2.81*	*2.43*	*2.42*	*2.57*	*4.88*	*5.23*	*5.24*	*4.46*

Table 3. Willow yields and dry matter allocation in aboveground biomass.

Station	Year	FM [t ha^{-1}]				DM [t ha^{-1}]				% DM (shoots)				% DM (leaves)			
		clone															
		1023	1047	1052	1054	1023	1047	1052	1054	1023	1047	1052	1054	1023	1047	1052	1054
Osiny	2004	33.7a	27.0a	34.5a	22.0b	16.6a	14.1a	17.2a	10.8b	84.3	78.6	77.9	81.3	15.7	21.4	22.1	18.7
	2005	23.8a	23.2a	25.5a	25.1a	12.6a	12.7a	13.7a	12.4a	87.8	88.6	84.4	88.4	12.2	11.4	15.6	11.6
	2006	20.1a	26.1a	22.6a	24.3a	10.0a	12.8a	11.0a	11.5a	78.8	76.9	76.3	80.0	21.2	23.1	23.7	20.0
	average	*25.9*	*25.4*	*27.5*	*23.8*	*13.1*	*13.2*	*14.0*	*11.6*	*83.6*	*81.5*	*79.5*	*83.2*	*16.4*	*18.6*	*20.5*	*16.8*
Grabów	2004	26.6a	24.6a	26.2a	28.5a	13.4a	12.7a	13.1a	14.0a	87.3	81.6	80.5	84.1	12.7	18.4	19.5	15.9
	2005	21.2a	19.0a	22.6a	23.6a	11.0a	9.4a	10.8a	12.1a	86.5	87.8	88.9	87.6	13.5	12.2	11.1	12.4
	2006	23.1a	23.0a	22.4a	26.6a	11.2a	11.2a	10.8a	12.7a	78.8	74.1	74.1	79.4	21.2	25.9	25.9	20.6
	average	*23.6*	*22.2*	*23.7*	*26.2*	*11.9*	*11.1*	*11.6*	*12.9*	*84.2*	*81.2*	*81.2*	*83.7*	*33.3*	*18.8*	*18.8*	*16.3*

FM – total yield (fresh mass), **DM** – yield of dry matter, **% DM (shoots)** – share of shoots in the yield of dry matter,
% DM (leaves) – share of leaves in the yield of dry matter.

-175 at Grabów caused the yields to drop by 13% and 19%, respectively, as compared to the yields in the previous year. In the driest year 2006 the yields were ca. 11.3 t DM ha^{-1} at Osiny and 11.5 t DM ha^{-1} at Grabów. That year had the highest water deficit (IV–VII) of -332 at Osiny and -359 at Grabów, although the annual amount of the deficit was somewhat alleviated by August rainfalls. Yields were lower by 23% and 14% at the two sites, respectively, compared to those in 2004.

In northern Poland, on the humus alluvial soil, at the density of 40 cuttings ha^{-1}, researchers from UWM Olsztyn reported that annual shoot yield of willow was 14.90 t DM ha^{-1} (Stolarski at al., 2002); 16.32 t DM ha^{-1} (Szczukowski at al., 2005); 17.25 t DM ha^{-1} (Szczukowski at al., 2004), 18.69 t DM ha^{-1} (Stolarski at al., 2007). Thus, the average yield on a soil that was very suitable to grow willow in Poland was 16.79 t DM ha^{-1}. The yield at Osiny (2004–2006) was lower by 23.2% and at Grabów by 29.3% than that obtained by the investigators from Olsztyn.

Fisher at al. (2005) found that the potential productivity of energetic willow in the conditions of eastern Europe on a very suitable soil is about 16.0 t DM ha^{-1} (13.8–18.1 t DM ha^{-1}). Clones investigated in the experiment achieved lower yields by 19.1% at Osiny and by 25.6% at Grabów than assessed by Fisher at al.

The moisture content of shoots was about 50% and was similar to values reported in the literature (Szczukowski at al., 2000, 2004, 2005).

Estimation of biomass components in energetic crops is important because biomass components influence the ultimate size of the economically valuable products over the course of growth. A growing plant may allocate acquired resources to its several components (roots, stool, shoots, branches and leaves). Allocation of resources is generally different between clones because of their genetic variability. Climate, and especially sun radiation, planting density and also man-made modifications of site such fertilization or management affect the allocation pattern. In the paper only clone effects were considered.

Dry matter allocation in aboveground biomass was rather diverse which was especially true of the year 2004, when leaf dry weight at the stage of full development was about 18% of the total aboveground dry biomass. Dry mass of shoots, measured in the period of harvest was 77.9–87.3% of the total aboveground biomass. In the following year the proportion of leaves in the biomass was not so appreciable – 12.5% on average (meanwhile shoots accounted for 84.4–88.9% of the total weight). In 2006, the biomass of leaves increased to 22.7% and the biomass of shoots ranged between 74.1–80% of the total aboveground biomass. Except the second year of the experiment, the greatest share of shoots in the biomass was found in clones 1023 and 1054.

High growth rate of individual clones, as well as of particular stools, increases competition between stools and causes stools to die. If stool mortality is high, there is a risk of biomass production to decrease, over a long term. Intense competition between stools can, however, be offset by frequent harvesting, preferably every year.

Observations of the experiment indicate that some clones had curved shoots and exhibited irregular branching, especially under high plant density which stimulated self-thinning. Because of that the assessments of dry matter allocation may be imprecise.

Actual stand productivity, at any time at a given site is determined by how well trees capture resources (Mead, 2005). A significant link in growth process is the conversion rate of solar radiation into harvestable biomass through the photosynthesis. Energy efficiency in natural ecosystems ranges from 0.1 to 0.5% (Odum, 1977). The efficiency in managed systems with coppiced trees like willow reaches the efficiency of many agricultural crops. This is largely due to high allocation to above ground parts and relatively low respiration cost of juvenile tissue (Cannell et al., 1987).

Table 4. Radiation use efficiencies by willow in 2004–2006.

Station	Clone	2004		2005		2006	
		regression equation	R^2	regression equation	R^2	regression equation	R^2
Osiny	1023	DM = -654 + 1,45 IPAR	98,90**	DM = -623 + 1,34 IPAR	83,83**	DM = 1,09 IPAR	98,73**
	1047	DM = -615 + 1,25 IPAR	94,35**	ns	-	DM = 1,12 IPAR	99,17**
	1052	DM = -642 + 1,51 IPAR	92,74**	ns	-	DM = 1,06 IPAR	99,02**
	1054	DM = -525 + 0,96 IPAR	89,45**	DM = -908 + 1,45 IPAR	70,76*	DM = 1,12 IPAR	99,44**
Grabów	1023	DM = -533 + 1,13 IPAR	98,90**	DM = -788 + 1,37 IPAR	96,16**	DM = 1,11 IPAR	98,79**
	1047	DM = -513 + 1,06 IPAR	96,30**	DM = -575 + 1,03 IPAR	86,44**	DM = 0,74 IPAR	98,17**
	1052	DM = -606 + 1,18 IPAR	88,35**	DM = -344 + 1,06 IPAR	94,02**	DM = 1,90 + 0,88 IPAR	98,73**
	1054	DM = -624 + 1,23 IPAR	92,36**	DM = -684 + 1,36 IPAR	87,99**	DM = 0,86 IPAR	98,86**

DM – dry aboveground mass of plant [g m^{-2}], IPAR – total incoming photosynthetically active radiation [MJ m^{-2}].
* significant at the level $\alpha = 0,05$; **significant at the level $\alpha = 0,01$.
ns – non significant.

Conversion efficiency is defined here as the ratio of the energy fixed in the aboveground dry mass produced to the total incoming photosynthetically active radiation (PAR).

From the slope of the above regression between absorbed photosynthetically active radiation and cumulative dry matter production accumulated on the basis of LAI, radiation use efficiency (RUE) was determined (as grams of dry matter biomass per MJ of radiation). Linear relationships between the described factors are shown in Table 4.

In 2004, estimated RUE values for all clones were between 0.96–1.51 $g_{dry\ matter}$ MJ^{-1} (1.29 g_{DM} MJ^{-1} average) at Osiny on the sandy clay loam, while at Grabów on the loamy sand they reached 1.06–1.23 g_{DM} MJ^{-1} (with a somewhat lower average – 1.15 g_{DM} MJ^{-1}). Such a tendency was observed in the subsequent experiment years. In 2005, in spite of deepening drought, RUE values increased and ranged between 1.34–1.45 g_{DM} MJ^{-1} (1.39 DM MJ^{-1} average) at Osiny and between 1.03–1.37 g_{DM} MJ^{-1} (1.20 g_{DM} MJ^{-1} average) at Grabów. In 2006, RUE values were the lowest and ranged between 1.06–1.12 g_{DM} MJ^{-1} (1.09 g_{DM} MJ^{-1} average) at Osiny and 0.74–1.11 g_{DM} MJ^{-1} (0.89 g_{DM} MJ^{-1} average) at Grabów.

Similar ranges were found by Cannell at al. (1987) for two-year old shoots grown at a density of 40 000 plants per ha – 0.99–1.38 g_{DM} MJ^{-1}. On the other hand, Bullard at al. (2002) reported 1.86–1.89 g_{DM} MJ^{-1} for one-year old shoots, Noronha-Sannervik at al. (2006) determined that RUE was 0.91 g_{DM} MJ^{-1} and according to Linderson (2007) the value was 1.0 g_{DM} MJ^{-1}. Matthews and Grogan (2001) assumed that RUE under the conditions of England amounts to 0.67 g_{DM} MJ^{-1} of the total sun radiation. Compared with that the mean assessed RUE in 2004 (a relatively humid year) in willow cultivated on a sandy clay loam at Osiny was 1.29 g_{DM} MJ^{-1} of absorbed photosynthetically active radiation which correspond to 0.64 g_{DM} MJ^{-1} of the total radiation.

CONCLUSIONS

1. The mean yield of a willow coppice was 12.9 t DM ha^{-1} on a sandy clay loam at Osiny and 11.9 t DM ha^{-1} on a loamy sand at Grabów. The highest yields were recorded in 2004 and the lowest in 2006. The aboveground biomass of different clones ranged from 9.4 (clone 1047, Grabów, 2005) to 17.2 t DM ha^{-1} (clone 1052, Osiny, 2004) which translates to about 47–86 MWh ha^{-1}.
2. The yields were lower by 23.2% in Osiny and by 29.3% in Grabów compared to those obtained in northern Poland on soils highly suitable for willow cultivation.
3. Mean values of basical biometric parameters of willow were: 8 shoots, 9 mm of shoot diameter, 2.53 m of shoot height. Significantly higher number of stems per stool was found for clone 1054 at Osiny. The lowest maximum leaf area index was found in 2004 and the highest in 2006, while clone 1052 had the highest rate of leaf area.
4. The dry biomass of shoots accounted for 74.1–88.9% of the aboveground dry biomass of willow. Except for the second year of the experiment the greatest share of shoots in the biomass was found in clones 1023 and 1054.
5. Solar radiation use efficiency by the willow was comparable to the values reported in the literature.

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