Pol. J. Environ. Stud. Vol. 28, No. 6 (2019), 4359-4367
DOI: *10.15244/pjoes/94812* ONLINE PUBLICATION DATE: 2019-07-29

Original Research

Extensive Willow Biomass Production on Marginal Land

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Received: 14 June 2018
Accepted: 3 September 2018

Abstract

In temperate climate zones, fast-growing willow species harvested in short harvest rotations of 3 to 10 years are an interesting source of biomass for energy or industrial purposes. The aim of this study was to determine morphological traits and biomass yields of three willow cultivars and three clones cultivated on three different types of marginal soils at two densities. Willow was grown in the Eko-Salix system, with no ploughing, with limited fertilization and cultivation measures, harvested in a 7-year rotation. The experiment showed that willow can be produced in the Eko-Salix system in extensive cultivation; however, the yield was strongly differentiated by the marginal soils and by the cultivars and clones under study and ranged from 4.4 to 17.8 Mg ha^{-1} year^{-1} DM. The mean yield from all the sites for all the cultivars and clones as well as planting densities in the experiment was 8.0 Mg ha^{-1} year^{-1} DM. The biomass yield obtained on peat-muck soil and humic alluvial soil was similar and significantly higher than on very heavy clay soil. The Ekotur cultivar gave plants with better morphological traits and the significantly highest mean yield (12.9 Mg ha^{-1} year^{-1} DM).

Keywords: *Salix viminalis*; *Salix alba*; Eko-Salix system; marginal soils; biomass yield

Introduction

As the EU's growing priority for renewable energy sources is driven by increased energy dependency, rising fossil fuel prices and the desire to protect the environment, the demand for energy from biomass, mainly wood, is increasing. Waste wood from forestry and municipal energy management may in future be supplemented with wood acquired from agricultural land as fuel for power or heating plants [1-5]. It can also be used for the production of liquid transport fuels [6-8]. The use of lignocellulosic biomass in integrated bio-refineries and second-generation fuel production technologies may develop commercially within a few years, leading to further growing demand for biomass, particularly wood. In this context, fast-growing tree species (willow and poplar) grown in short rotation coppice (SRC) or short rotation forestry (SRF) systems and harvested in short rotations of 3 to 10 years are of interest for agriculture in temperate climate zones [9-11]. This type of plantation management includes regrowth of shoots from a trunk or a stool and the continuity of yield formation in successive rotations. Planted trees are used for agricultural purposes as a long-term plantation for over 20 years.

These crops may be taken into account in a concept of extensive agriculture, especially on marginal soils,

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Fig. 1. Location of field experiments.

which are of little use or unusable for growing food crops (periodically flooded or difficult in cultivation), periodically excluded from use and some fallow lands. In order to restore the land for use, the authors made an innovative – relative to the commonly used (SRC) [3, 12-15] – attempt to grow willow in the Eko-Salix system [11, 16]. The new concept of growing willow eliminates ploughing, makes use of long rods, limits fertilisation and care procedures and plants are harvested in a long, more than 5-year rotation.

The novelty of this study consists of demonstrating that extensive willow plantation can be set up with three-year-old rods growing at a density of 5,200 and 7,400 plants ha^{-1} on three types of marginal soil: riparian alluvial, very heavy mineral and organic, periodically excessively wet; moreover, in identifying new cultivars or clones of willow whose rods that take root well, grow fast and give a large yield of woody biomass when harvested in a long rotation. Therefore, the aim of this study was to determine the morphological traits and biomass yield of three cultivars and three clones of willow grown at three different sites with marginal soil with no ploughing, with limited fertilisation and cultivation measures and harvested in a 7-year rotation.

Material and Methods

The Experiment Sites

Three field experiments were located in northern Poland. One in the village of Obory (53°43’36.11’’N, 18°54’3.03’’E) in the Valley of Kwidzyn in the northern section of the Lower Vistula Valley, between Kotlina Grudziądzka and Żuławy Wiślane. The other two in the villages of Kocibórz (54°0’42.57’’N, 21°11’2.58’’E) and Leginy (54V0’2.75’’N, 21°7’55.92’’E), in the Mazury Lake District (Fig. 1). The research stations in which the experiments were set up are owned by the University of Warmia and Mazury in Olsztyn (UWM). The total annual rainfall at the village of Obory (average of 500 mm) was much smaller than at Kocibórz and Leginy (an average of 700 mm) (Fig. 2). The average air temperature at all the experiment sites was approx. 8ºC, and the growing season lasted 200-210 days. The total rainfall during the growing season (April-October) during the experiment ranged from 374 to 445 mm at Obory to 447 to 613 mm at Kociborz and Leginy. Meanwhile, the average air temperature during the growing season was similar and ranged from 13.1 to 14.5ºC.

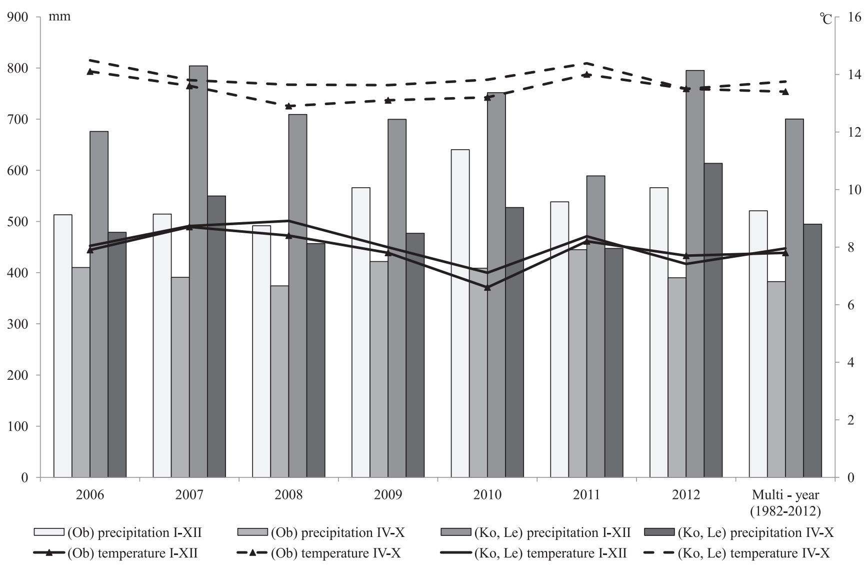

Fig. 2. Weather conditions during the experimental period 2006-2012 and multi-year period 1982–2012; bars represent precipitation; curves represent air temperatures (Ob = Obory; Ko = Kocibórz; Le = Leginy; I–XII = January–December; IV–X = April–October, growing season).

The experiment at the Obory site was conducted on riparian, alluvial soil, classified as heavy complete humic alluvial soil. The surface horizon (Ap 0-35 cm) of black medium silty clay contained 8.35% of organic matter and was neutral (pH_{KCl} 7.2) (Table 1). It was good-quality soil, with a high groundwater level, which made it periodically marshy. Therefore, it was suitable for growing crops requiring fertile and wet sites, including willow. The experiment at Leginy was conducted on marginal, very heavy mineral clay soil. The soil horizon (Ap 0-32 cm) contained more than 10% of organic matter, 0.21% of calcium carbonate, and was of neutral pH. It was fertile, very heavy soil and very difficult to cultivate. The experiment at Kocibórz was

Table 1. Characteristics of soils at the three locations: Obory, Leginy and Kocibórz.

	Obory		Leginy		Kocibórz
Type of soil	Riparian, heavy, complete humic alluvial soils.	Type of soil	Mineral, very heavy clayey soil, black-brown soil.	Type of soil	Organic, peat-muck soil, formed from alder peat and reed peat on detrital-calcareous gyttja, medium decomposed.
Location	Plain with poor outflow.	Location	Plain with good outflow.	Location	Plain with good outflow.
Ap 0-35 cm	Medium silty clay, black when fresh (10Y 2/1), contains 8.35% of organic matter, pH_{KCl} 7.2.	Ap 0-32 cm	Clay, olive brown (7.5Y 3/2 wet); contains 10.27% of organic matter, neutral soil reaction (pH_{KCL} 7.0); contains 0.21% of $CaCO_3$, clear horizon boundary.	Mt1 0-23 cm	Proper muck, ash content 54.71%, black (7.5Y 2/1 wet); neutral soil reaction (pH_{KCL} 6.8); clear horizon boundary.
ACG1 35-80 cm	Medium silty clay, with gleyed mottles, olive-black when fresh (10Y 3/1), contains 9.90% of organic matter, pH_{KCl} 7.2.	Bbrg 32-80 cm	Clay with gleyed mottles, olive-brown; neutral soil reaction (pH_{KCL} 7.0); contains 5.78% of $CaCO_3$, gradual horizon boundary.	OtniolR3 23-56 cm	Strongly decomposed alder peat (R_3), with wood and reed remnants; ash content 26.63%; black-brown (2.5Y 3/1 wet); neutral soil reaction (pH_{KCL} 6.7); clear horizon boundary.
ACG2 80-150 cm	Loamy silt, with zones of gley, olive black when fresh (7,5 3/1), contains 14.3% of organic matter, pH_{KCl} 7.0.	Ccag 80-150 cm	Clay with gleyed mottles, olive-brown (2.5Y 4/3 wet); neutral soil reaction (pH_{KCL} 7,0). contains 14.93% of $CaCO_3$	OtniszR2 56-100 cm	Medium decomposed reed peat (R_2), ash content 8.80%; black (7.5Y 2/1 wet); neutral soil reaction (pH_{KCL} 6.6); clear horizon boundary.
				OtniszR2 100-160 cm	Slightly decomposed reed peat (R_1), ash content 8.29%; black (10Y 2/1 wet); neutral soil reaction (pH_{KCL} 6.7); contains 0.29% $CaCO_3$, clear horizon boundary.
				OtniszR2 160-250 cm	Detrital-calcareous gyttja (calcareous), grey-olive (7.5Y 5/2 wet); contains 23.26% of organic matter, contains 52.34% of $CaCO_3$, clear horizon boundary.
				OtniszR2 250-370 cm	Detrital-calcareous gyttja (calcareous), grey-olive (7.5Y 4/2 wet); contains 21.03% of organic matter, contains 48.04% of $CaCO_3$, clear horizon boundary.
				Otnisz R2 370-480 cm	Detrital-calcareous gyttja (calcareous), grey-olive (7.5Y 4/2 wet); contains 17.60% of organic matter, contains 48.86% of $CaCO_3$, clear horizon boundary. Sandy loam.
				< 480 cm	Peat-muck soil formed from alder and reed peats, on detrital-calcareous gyttja, medium advanced muck-forming process [Ł – MtII cb].

conducted on organic, peat-muck soil formed from peat, periodically excessively wet. The surface horizon of 0-23 cm was peat much proper with ash content of over 54% and neutral pH (pH_{KCl} 6.8). A detailed description of the soil profiles is shown in Table 1.

The groundwater level during the growing season in Obory was 40-81 cm, in Leginy 150-220 cm, and in Kocibórz 10-50 cm. Alfalfa was grown as a forecrop at Obory and Leginy and extensively used grass at Kocibórz. In late autumn of 2005, before the willows were planted, alfalfa and plants on the grassland were mowed and left in the field.

The Experiment

The experiment was conducted from 2006 to 2012. It was set up in a split-block-split-plot design in four replications. Three marginal sites were the first factor (A): Obory, Kocibórz and Leginy. Three willow cultivars: Turbo (*Salix viminalis* L.), Tur (*Salix viminalis* L.), Ekotur (*Salix viminalis* L.) and three clones: UWM 046 (*Salix viminalis* L.), UWM 095 (*Salix alba* L.) and UWM 200 (*Salix alba* L.) – all bred at the Department of Plant Breeding and Seed Production of the UWM – were the second factor (B). Rod planting densities of 5,200 and 7,400 plants ha^{-1} was the third factor (C).

Twin row planting was applied in the first variant (I – 5,200 ha^{-1}) with a space of 0.75 m between two rows in a stripe, and subsequently a space of 1.8 m and another two rows with a space of 0.75 m between them (Fig. 3). There were two rows in each plot

Fig. 3. Seven-year-old willows cultivated at a density of 5,200 plants ha^{-1} in the Eko-Salix system.

Fig. 4. Seven-year-old willows cultivated at a density of 7,400 plants ha^{-1} in the Eko-Salix system.

(38.3 m^2), and there was a space of 1.5 m between rods in a row. Inter-row spaces of 1.8 m were applied in the second variant (II – 7,400 ha^{-1}) (Fig. 4). There were two rows in each plot (54 m^2), and there was a space of 0.75 m between rods in a row. Rods (2.4 m long) were obtained from three-year willow shoots; they were rootless and they were planted with a water drill at a depth of 0.4 m and soil was pressed thoroughly to the seedling.

Mineral fertilisation was not applied in the first year (2006); the following fertilisers were sown manually in the spring of the second and third years: N 40 $kg \cdot ha^{-1}$ as ammonium nitrate; P 9 $kg \cdot ha^{-1}$ as triple superphosphate; and K 33 $kg \cdot ha^{-1}$ as potassium salt. Cultivation measures during the first two years of the experiment were limited to two mowings of weeds in inter-row spaces with a brushcutter. No cultivation measures or fertilisation were applied in the subsequent years (4^{th}-7^{th}) of the experiment.

Determining Plant Density, Biometric Traits and Biomass Yield

After the end of the seventh growing season in 2012, plant density was determined on plots and expressed as the number of plants per ha. Biometric measurements were conducted on 10 plants per plot, taking into account: plant height, shoot diameter (measured at breast height, i.e. 1.3 m), and number of 1^{st}-order branches.

The biomass yield after seven growing seasons was determined by weighing the fresh biomass from each plot and calculating the biomass yield per 1 ha. Willows of each cultivar were cut up with a chipper and representative samples were taken for laboratory analyses. The moisture content in biomass was determined by drying at 105°C and weighing. Wood chips were dried until their weight was constant. The dry biomass yield was calculated from the moisture content and fresh biomass yield.

Statistical Analysis

The analysis of variance split-plot-split-block design was carried out to determine the main effects of site (factor A), variety or clone (factor B), planting density (factor C) for the morphological features and the willow yield. The level of significance of the analysis was established at $P<0.05$. Homogeneous groups for the examined traits were determined by Tukey's (HSD) multiple-comparison test. Arithmetic mean and the standard error of mean (SEM) were calculated for the traits under study. All statistical analyses were done with STATISTICA 13.3 software.

Results and Discussion

There were an average of 5,313 plants ha^{-1} after the end of the seventh growing season in 2012 (Table 2). The number of plants growing on humic alluvial soil in Obory was significantly less than in Kocibórz and Leginy, where willow grew on peat-muck soil and on very heavy clay soil. The density of the Ekotur cultivar and the UWM 095 clone was similar and significantly higher (homogeneous group a) than of the other cultivars and clones under study (homogeneous group b). The number of plants at the two planting densities under study varied significantly, as expected.

An average of over 15% of willow were lost after seven growing seasons (Table 2). The percentage was similar in Kocibórz and Leginy and significantly smaller than in Obory. It was smaller in the Ekotur cultivar than in the UWM 095 clone and significantly smaller than in the other cultivars and clones. At a higher initial planting density (7,400 ha^{-1}), the willow mortality was significantly higher (17.4%) compared to the lower planting density.

The average height of the seven-year-old willows grown out of the live stakes was 8.6 m, with the main stem growing 0.94 m a year on average (Table 3). The height of the plants in Obory and Kocibórz was in the same homogeneous group (a), and it was significantly greater than in Leginy. The Ekotur cultivar gave the highest plants (mean – 10.0 m) – significantly higher than the UWM 046 clone. No significant differences were found between the height of plants growing at the two densities under study.

The mean diameter of the main willow stem measured at the breast level (1.3 m) after the end of the growing season in 2012 was 6.6 cm, and the annual gain of the stem thickness was 0.66 cm (Table 3). The stem thickness was identical at Obory and at Kociborz and significantly higher than at Leginy. The stem diameters measured in the Ekotur cultivar and the UWM 095 clone were not different and were significantly higher than in the UWM 046 clone. The mean number of 1st-order branches per plant was 2.3. This trait was poorly diversified and ranged from 1.9 to 2.7.

The mean fresh biomass yield after seven years of cultivation in the experiment was 111.8 Mg ha^{-1} (Table 4). The highest yield was obtained at Kocibórz – higher by 44.0 Mg ha^{-1} than at Leginy. The fresh woody biomass yield obtained from the Ekotur cultivar (179.0 Mg ha^{-1}) was significantly higher than from the UWM 095 clone and was significantly higher than from the Turbo and Tur cultivars and the UWM 046 clone (homogeneous group c). The lowest biomass yield was obtained from the UWM 200 clone (67.8 Mg ha^{-1}, homogeneous group d). The biomass yield obtained at the higher willow density (7,400 ha^{-1}) was slightly larger

Table 2. Number of plants and mortality rate after 7 years of growth.

Item		Number of plants ha^{-1}	Mortality rate (%)
Site	Obory	4,904.5±728.7 B	21.7±6.6 B
	Kocibórz	5,386.9±933.6 A	14.5±4.4 A
	Leginy	5,647.0±973.5 A	10.4±2.6 A
Variety or clone	Turbo	5,149.3±904.8 b	18.2±4.1 b
	Tur	5,222.0±969.0 b	17.2±4.8 b
	Ekotur	5,679.0±1001.7 a	9.8±5.0 a
	UWM 095	5,460.7±933.3 a	13.2±4.0 a
	UWM 200	5,118.5±990.5 b	18.6±8.3 b
	UWM 046	5,247.4±979.5 b	16.3±9.5 b
Planting density (plants ha^{-1})	5,200	4,517.1±275.4 b	13.6±5.3 b
	7,400	6,108.5±551.8 a	17.4±7.5 a
General mean value		5,312.8±914.3	15.5±6.7

±SEM standard error; A,B,C… homogenous groups for sites; a,b,c… homogenous groups for varieties or clones; *a,b,c…* homogenous groups for planting densities

Table 3. Plant height, stem diameter, and number of branches of willow plants.

Item		Plant height (m)	Stem diameter (cm)	Number of branches
Site	Obory	9.5±1.3 A	7.2±1.4 A	2.6±0.2 A
	Kocibórz	9.0±1.1 A	7.2±1.8 A	2.0±0.4 B
	Leginy	7.2±0.7 B	5.3±0.9 B	2.2±0.4 B
Variety or clone	Turbo	8.2±1.0 b	5.9±0.9 b	2.4±0.3 b
	Tur	8.5±1.2 b	5.7±1.1 b	1.9±0.5 c
	Ekotur	10.0±1.5 a	8.3±1.6 a	2.3±0.5 b
	UWM 095	9.4±1.6 a	8.4±1.5 a	2.3±0.3 b
	UWM 200	7.9±1.0 b	5.7±0.5 b	1.9±0.4 c
	UWM 046	7.4±0.9 c	5.4±0.9 c	2.7±0.2 a
Planting density (plants ha^{-1})	5,200	8.3±1.4	6.8±1.8	2.3±0.5
	7,400	8.8±1.4	6.3±1.5	2.2±0.4
General mean value		8.6±1.4	6.6±1.7	2.3±0.4

± SEM standard error; A,B,C… homogenous groups for sites; a,b,c… homogenous groups for varieties or clones

(the difference not demonstrated statistically) than at the density of 5,200 ha^{-1}.

The mean dry wood yield from 7-year-old willows was 56.0 Mg ha^{-1} DM (Table 4). The yield obtained at Kociborz was higher by 7.1 and 22.2 Mg ha^{-1} DM than at Obory and Leginy, respectively. The new Ekotur cultivar gave the highest yield (mean – 90.0 Mg ha^{-1} DM), which was significantly higher than the UWM 095 clone and the other cultivars and clones. The yield obtained from willows growing at the density of 5,200 ha^{-1} was lower by 2.6 Mg ha^{-1} DM than from willows growing at the density of 7,400 ha^{-1}.

The yield of dry woody biomass obtained in the Eko-Salix system, calculated per year of plantation use, was differentiated strongly by the type of the marginal soil, the cultivars and clones under study and by interactions between these factors. It ranged from 4.4 to 17.8 Mg ha^{-1} year^{-1} DM (Fig. 5). The new Ekotur cultivar gave the highest yield at the three sites under study, but the amount of wood obtained from them varied significantly. It gave the highest mean yield at Kocibórz, where plants grew on peat-muck soil (over 17.0 Mg ha^{-1} year^{-1} DM). It gave a yield lower by 24% at Obory (humic alluvial soil) and by 53% at

Table 4. Fresh and dry biomass yield of willow biomass at harvest.

Item		Fresh matter yield (Mg ha^{-1})	Dry matter yield (Mg ha^{-1} DM)
Site	Obory	117.3±48.0 A	58.7±23.4 A
	Kocibórz	131.0±57.4 A	65.8±28.4 A
	Leginy	87.0±20.2 B	43.6±9.5 B
Variety or clone	Turbo	99.2±14.7 c	50.9±7.7 c
	Tur	91.4±18.4 c	48.4±10.0 c
	Ekotur	179.0±57.6 a	90.0±28.8 a
	UWM 095	145.7±31.9 b	69.1±15.2 b
	UWM 200	67.8±4.2 d	32.3±1.2 d
	UWM 046	87.7±15.4 c	45.5±8.7 c
Planting density (plants ha^{-1})	5,200	109.4±49.2	54.7±24.3
	7,400	114.2±46.6	57.3±22.9
General mean value		111.8±47.3	56.0±23.3

±SEM standard error; A,B,C… homogenous groups for sites; a,b,c… homogenous groups for varieties or clones

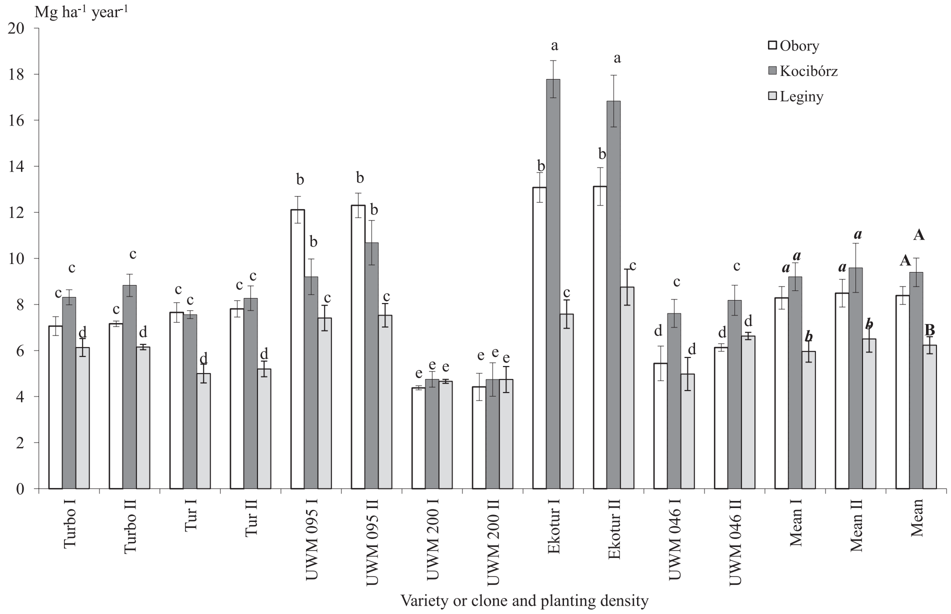

Fig. 5. Yield of willow biomass (Mg ha^{-1} year^{-1} DM) at three experimental sites in relation to genotype and planting density; bars represent standard error values (SEM); (I) 5,200 and (II) 7,400 initial planting densities, plants ha^{-1}; a, b, c… homogeneous groups.

Leginy (very heavy clay soil). On the other hand, the UWM 095 clone gave a higher yield at Obory than at Kociborz (homogeneous group b at both sites) and significantly lower at Leginy (homogeneous group c). When harvested in a 7-year rotation, the Turbo and Tur cultivars gave a low yield of woody biomass both on alluvial soil (Obory) and on organic soil (Kocibórz) (homogeneous group c at both sites c) and very low yield on heavy soil (Leginy; homogeneous group d). The UWM 200 clone gave a very low yield at all three experimental sites (homogeneous group e).

The experiment has demonstrated that willow can be grown in the Eko-Salix system with 3-year-old rods planted at 5,200 and 7,400 ha^{-1} on three types of soil: riparian alluvial soil (Obory), very heavy mineral soil (Leginy) and organic soil (Kocibórz). However, the choice of site and the willow cultivars had a significant effect on the growth and development of the crop harvested in a 7-year rotation. Kocibórz and Obory, with their high level of groundwater (but not stagnant), had favourable conditions for plant growth. On the other hand, not scarified and not ploughed soil at Leginy, poorly aerated and with a low level of groundwater (150-220 cm) during the experiment, had much less favourable conditions for growing willow. The mean yield of dry wood at this site was lower than at Kocibórz and Obory, by 34% and 26%, respectively.

A very high yield of small-sized wood in the 7-year rotation was obtained in this experiment from the Ekotur cultivar at Kocibórz and Obory at 17.3 and 13.1 Mg ha^{-1} year^{-1} DM, respectively. But the yield of this cultivar was much lower at Leginy. A similar relationship was observed in the UWM 095 clone, but it gave a much lower yield than Ekotur. It has been shown in earlier studies [11, 17] that the UWM 043 clone (currently the Ekotur cultivar) and the Duotur cultivar (currently the UWM 095 clone) were highly productive at Kocibórz and Obory when grown in short, 3- and 4-year harvest rotations: 15 and 12 Mg ha^{-1} year^{-1} DM, respectively. The Tur cultivar and the UWM 046 clone was grown in a short 3-year rotation on humic alluvial soil at Obory, which also gave high yields of over 10 Mg ha^{-1} year^{-1} DM, and approx. 8 Mg ha^{-1} year^{-1} DM when grown in a 4-year rotation on peat-muck soil (Kocibórz). However, they did not show such high productivity in the 7-year rotation analysed in this study; their yield was much lower, especially at Leginy. The Corda cultivar (currently the UWM 200 clone), when harvested in short 3- and 4-year rotations, gave satisfactory yield [11, 17], whereas its productivity was very low when it was harvested in a long 7-year rotation (4 Mg ha^{-1} year^{-1} DM). This shows low usability of the Tur and Turbo cultivars and he UWM 046 and UWM 200 clones in cultivation in the Eko-Salix system in an extended 7-year harvest rotation. Ekotur and UWM 095 grown in a 7-year harvest rotation gave thick shoots of a similar diameter at over 8 cm. The height of the willows after seven years was approx. 10 m (the rods were 2.0 m long when planted), i.e., an annual increase was approx. 1.0 m.

It must also be emphasized that the choice of the willow rotation in the Eko-Salix system will depend on the end-user's requirements regarding the quality of wood (i), the method of harvest (ii), rate of return on investment (iii), and number of rotations (iv).

(i) It has been shown in earlier studies [18, 19] that willow biomass obtained in short 3- and 4-year harvest rotations is of lower quality compared to that from 5-7-year rotations because of a higher bark content.

(ii) 3- or 4-year willow shoots can be harvested, for example with a Claas Jaguar harvester, whereas with a 7-year rotation a special machine must be used that will harvest and cut up thick shoots, e.g., a forwarder fitted out with a Mecanil EG250A felling head and a cutting knife installed on [16, 20].

(iii) The rotation length and the willow cultivar are of particular importance because they affect the economic output of the whole project [21, 22]. Considering the argument of a fast return on investment, the harvest rotation for an SRC should be 3-4 years. However, growing energy crops in the Eko-Salix system on marginal soils, with low usability in cultivation of food crops, can also be profitable in longer harvest rotations.

(iv) The number of rotations and the duration of plantation use will also affect the economic outcome of an enterprise. Studies must be continued to determine the shoots' ability to grow off a stool and the willow yield in successive extended 7-year rotations at the marginal soil sites under study.

Currently, willow production in a short 3-4 year harvest rotation dominates on agricultural soils (SRC) [12, 13, 23, 24]. Preparation of soil for planting the cuttings includes typical agrotechnical measures (ploughing, fertilisation, cultivation). Cuttings (approx. 0.20 m long) are planted in a twin row configuration. The distance between rows is 0.75 m and between stripes – 1.5 m. Cuttings in rows are usually planted every 0.5 m, which gives the planting density of 18,000 plants ha^{-1}. Short-rotation willow output achieved in field experiments conducted in optimum conditions in Poland reached 30 Mg ha^{-1} $year^{-1}$ DM [25, 26]. The mean yield in experiments conducted in Poland has usually ranged from 10 to 12 Mg ha^{-1} $year^{-1}$ DM [27, 28]. Furthermore, the mean yield of willow on commercial plantations has been, in general, much lower – 7 Mg ha^{-1} $year^{-1}$ DM – ranging from 3 to 14 Mg ha^{-1} $year^{-1}$ DM [20, 29]. Similar mean yields of willow (but varied depending on the factors under analysis) grown in the SRC system in commercial plantations have been obtained in Denmark, Sweden and the UK [10, 24, 30, 31].

Conclusions

The current study has shown that growing demand for biomass, mainly for wood, can be partly satisfied by alternative growings of willow in the Eko-Salix system, which can reduce its shortage on the market. Wood can be acquired outside the forest, on marginal areas, not used in agricultural production, which currently is wasteland despite frequently fertile soils. This applies mainly to riparian alluvial soils, organic soils, land which is under erosion and difficult to cultivate – often with a large area. Growing willow in the Eko-Salix system in some such areas can be important from an economic point of view. In conclusion, it has been demonstrated that small-sized willow wood can be produced in the Eko-Salix system using extensive measures (no ploughing, limited fertilisation and cultivation measures) with three-year-old rods on three types of marginal soil. The Ekotur (*Salix viminalis*) cultivar and the UWM 095 clone (*Salix alba*), whose mortality after 7 years was relatively low, have 10 m-tall plants with a shoot diameter exceeding 8 cm, with particularly high yields on peat-muck soil and humic alluvial soil.

Acknowledgements

This paper is the result of a long-term study carried out at the University of Warmia and Mazury in Olsztyn, Faculty of Environmental Management and Agriculture, Department of Plant Breeding and Seed Production, topic number 20.610.008–300 and it has been co-financed by the National (Polish) Centre for Research and Development (NCBiR), entitled "Environment, agriculture and forestry," project: BIOproducts from lignocellulosic biomass derived from MArginal land to fill the Gap In Current national bioeconomy, No. BIOSTRATEG3/344253/2/NCBR/2017.

Conflict of Interest

The authors declare no conflict of interest.

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