Original Research

Dendromass Derived from Agricultural Land as Energy Feedstock

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Abstract

In order to ensure consistent supplies of agriculture-derived lignocellulosic biomass for the emerging biomass market, dedicated plantations of short rotation woody crops (SRWC) need to be developed. Our research aimed at defining the yield, survivability, and morphological features of three plant species (SRWC) cultivated under the conditions of northeastern Poland, on poor soil unsuitable for food or fodder crops. The first factor for the experiment was provided by three plant species: willow (*Salix viminalis* L. UWM 006), poplar (*Populus nigra* × *P. Maximowiczii* Henry cv. Max-5), and black locust (*Robinia pseudoacacia* L.). The second factor consisted of seven soil enrichment regimes, referred to as "fertilization," and a control. Willow grew significantly the highest. Poplar grew to a similar height and the diameter of its shoots was significantly the biggest. The yield varied significantly depending on plant species and soil enrichment regime. During a two-year rotation cycle of the crops, poplar and willow produced notably higher yields than black locust, despite growing on poor soil. The soil enrichment regimes, in turn, significantly improved the crop yields.

Keywords: willow, poplar, black locust, lignocellulosic biomass, yield, biometric features

Introduction

Biomass is an important industrial and energy resource. Among renewable energy sources, biomass accounts for the highest percentage share globally, in the EU, and in Poland (62.5%, 46.0%, and 86.1%, respectively) [1-3]. Lignocellulosic biomass is currently obtained from woodland, the timber industry, and urban greenery care. In the future, dedicated perennial field crops, specifically short rotation woody crops (SRWC), will be one of the key sources of lignocellulosic biomass. In warmer climatic zones they include species within the type of eucalyptus (*Eucalyptus* L'Hér.) [4, 5] and paulownia (*Paulownia* Siebold & Zuccarini) [6]. Black locust (*Robinia pseudoacacia* L.) also prefers warmer climatic zones, although it is cultivated in mild climates, too [7-10]. Species within the type of *Salix* and *Populus*, however, have a wide growing range [11-19]. SRWCs, besides providing biomass for energy generation, play an important role in reclamation of contaminated land. Moreover, they can be fertilized with sewage sludge [20-23].

The demand for non-woody lignocellulosic biomass will rise significantly both in Poland and in the EU. In Poland, there is further demand driven by the regulation passed by the polish minister of the economy on 14 August 2008, with subsequent amendments [24, 25]. In this document, the percentage of renewable energy is forecast to rise, and the use of non-woody biomass for energy production

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purposes is expected to increase substantially. In 2012 the percentage of biomass derived from non-woody sources, mainly from agriculture and the food industry, and used in power plants with biomass co-combustion generating over 5 MW, should reach at least 55%. This percentage is expected to rise up to 70% in 2013, 80% in 2014, and 100% after 2015. In the case of hybrid systems and units that will combust only biomass in units of electric power above 20 MW, the percentage of non-woody biomass is projected to be around 20% in 2012, rising to 60% after 2017. This increase in the use of non-woody biomass for energy purposes and, consequently, reduced combustion of woody biomass imposed by the above regulation, can be said to be justifiable and rational as forests and timber obtained from forests should have other functions. Power plants prefer lignocellulosic biomass as an energy resource. In view of the above considerations, there is still some concern that the growth of lignocellulosic biomass use for energy purposes may cause shortages of woody resources for industrial purposes, e.g. for production of cellulose, paper, and wooden boards [26]. Consequently, in order to ensure reliable future supplies of agriculture-derived lignocellulosic biomass for the emerging market, dedicated plantations of SRWC need to be developed. These plantations should be established on soil that is sub-standard for food and fodder crops.

In view of the above, the aim of this paper has been to define the yield, survivability, and morphological features of three plant species cultivated in northeastern Poland, on poor soil unsuitable for production of food crops or fodder crops.

Material and Methods

Soil Characteristics

The experiment was located in northeastern Poland near the village of Samławki (53°59′ N, 21°04′ E). As assumed in the research methodology, relatively poor soil was chosen for evaluation of the potential yield of three species depending on the applied soil enrichment regime. Although the experimental field was relatively flat, it lay on the crest of a hill in an undulating landscape of varied land relief. The soil analyses indicated that the experiment was located on brunic arenosol (dystric) soil developed from loose sand. Loamy sand was found in humus A (0-21 cm) and enriched soil Bv (21-41 cm) horizons, whereas the native rock C (41-150 cm) layer contained loose sand. The content of floatable particles in the particular soil horizons did not exceed 6%. The soil was periodically dry and groundwater was found much below 150 cm. Thus, the experiment was set up on soil that was substandard for traditional agricultural production of food or fodder crops.

The soil was neutral to alkaline in reaction (pH_{KCl} 6.3-7.9) (Table 1). The content of organic matter in the topmost layer was 2.89%, which provided it with a resource of 114.1 $Mg\cdot ha^{-1}$, another proof that the soil was of little use for agricultural purposes. Air and water properties largely depend on the organic matter content and grain size distribution of soil. The soil in the present experiment was characterized by poor air and water properties. The content of mesopores, which determine the availability of water to plants, was low in its topmost layers, consisting of loamy sand, and very low in the underlying loose sands. When combined with the lack of rainfall, such characteristics caused continuous shortage of water for plants. Macropores dominated in the overall soil profile (19.3-30.42%). The determination of nutrients in the humus showed a very high content of phosphorus and magnesium and high potassium content. In the enrichment level (Bv), the content of phosphorus was high, potassium was medium and magnesium was very high. The native rock had a low content of all the three elements. The comparatively high nutrient content in the humus and enrichment level resulted from prior plouwing and intensive fertilization applied under cereal crops that used to be grown on this field.

Table 1. Physico-chemical parameters of soil.

Parameter	Unit	Horizon (cm)		
		A (0-21)	Bv (21-41)	C (41-150)
Macropores	Ø>30 μm, %	19.30	22.75	30.42
Mesopores	Ø>30-0.2 μm, %	14.80	15.82	10.32
Micropores	Ø<0.2 μm, %	1.82	3.42	1.97
pH (KCl)	-	7.05	6.30	7.92
Organic matter	%	2.89	-	-
	$Mg\cdot ha^{-1}$	114.1	-	-
N	$mg\cdot kg^{-1}$	3.90	1.10	0.51
P	$mg\cdot kg^{-1}$	25.5	15.3	9.6
K	$mg\cdot kg^{-1}$	12.8	9.6	2.6
Mg	$mg\cdot kg^{-1}$	6.6	7.6	2.3

Setting up and Running the Experiment

The preceding crop for willow, poplar, and black locust cultivated between crop rotations was triticale. Following the triticale harvest, the herbicide Roundup was sprayed in a dose of 5 $dm^3\cdot ha^{-1}$. Approximately three weeks later, the field underwent soil disking, and in late autumn 2009 it was ploughed to a depth of 30 cm. In spring 2010 the field was harrowed and marked for planting. Willow and poplar cuttings as well as black locust seedlings were manually planted. The cuttings were 25 cm long and of 0.9-1.1 cm in diameter, whereas rooted black locust seedlings were approximately 30-35 cm in height.

The stage that followed the planting of willow and poplar cuttings was the application of Guardian Comlete MIX 664 SE herbicide mixed with water in a 3.5:300 $dm^3\cdot ha^{-1}$ ratio. The preparation was not used on plots with black locust. During the growing season in 2010, mechanical plant pruning was performed three times on each plantation.

A strict, two-factor field experiment conducted in the 3rd decade of April 2010 at the Research Station in Łężany of the University of Warmia and Mazury in Olsztyn provided the research results presented in this paper.

The first factor of the experiment was the three plant species: willow, poplar, and black locust. The willow clone of *Salix viminalis* L., UWM 006 originated from the collection of the Department of Plant Breeding and Seed Production at the University of Warmia and Mazury in Olsztyn; *Populus nigra* × *P. Maximowiczii* Henry cv. Max-5 poplar came from a farmstead in northern Austria. Finally, black locust (*Robinia pseudoacacia* L.), as a native species, came from a domestic plant nursery.

The second factor consisted of soil enrichment regimes, referred to as "fertilization." According to the assumed methodology, the following were applied: lignin (L), mineral fertilization (F), micorysis vaccination (M), lignin + mineral fertilization (L + F), micorysis + mineral fertilization (M + F), lignin + micorysis (L + M), and lignin + micorysis + mineral fertilization (L + M + F). There was also a control treatment with no soil enrichment (C).

The experiment was started at a density of 11,111 of plants per ha. A strip cropping system was used, i.e. two rows at 0.75 m in a strip, then a 1.5 m intercrop strip separating two subsequent rows in another strip at the same inter-row space of 0.75 m, etc. The distance between plants in a row was 0.80 m. The experimental plot was divided into three subplots of 18.0 m^2 each.

Lignin, a by-product of paper production, was applied in a dose of 13.3 $Mg \cdot ha^{-1}$ in the spring preceding the experiment. It was spread over the soil surface with a fertilizer spreader prior to soil plating and plouwing. Subsequently, it was mixed with the soil and incorporated deep into the soil profile. The applied lignin contained 61.72% of organic matter and had a high acid reaction. The phosphorus and potassium content was very low and the magnesium content was low.

Mycelium was applied separately for each of the species between 1 and 10 of September 2010, when the willow, poplar, and black locust crops were sufficiently well rooted. Liquid vaccination of 30-35 cm^3 was applied underneath each of the crops using a hand-operated instrument. A single injection was made into the soil close to each plant earmarked for micorysis, and plants were vaccinated as close to the roots as possible.

Mycelium used for willow micorysis vaccination originated from multiplication of mycelium separated from roots of *Salix caprea* willow growing in Augustowska Forest (Puszcza Augustowska) in Poland. Poplar was vaccinated with micorysis isolated from roots of energy poplar growing on a Spanish plantation, which had been treated with micorysis isolated from poplars growing in Słowiński National Park in Poland, i.e. it was the case of re-isolation. Black locust was vaccinated with a mixture of mycelium used in forestry. This plant does not generate species-specific micoryses and its roots cohabit with a variety of fungi.

In the first year, no mineral fertilization was applied due to the slow development of the plants' roots. Before the second growing season started (spring 2011), phosphorus and potassium were manually spread. Phosphorus was applied as triple superphostate in a dose of 13 $kg \cdot ha^{-1}$, and potassium was applied as potassium salt in a dose of 50 $kg \cdot ha^{-1}$. Additionally, nitrogen was applied twice. The first rate (50 $kg \cdot ha^{-1}$ of ammonium nitrate) was applied immediately before the plant growing season of 2011 began. The second rate of nitrogen, in the same form but in a dose of 40 $kg \cdot ha^{-1}$, was applied between 10 and 20 June 2011.

Biometric Measurements and Yield

When the first (2010) and the second (2011) plant growing seasons finished, in the first decade of December, the crop yield was determined in respective subplots and calculated per ha. Additionally, green shoots over 1.5 m long were counted on each plant. On every subplot, 10 plants underwent biometric measurements of height and shoot diameter (at 0.5 m height). In order to assess the yield, in December 2011, i.e. after the second vegetative season, whole plants were cut manually 5-10 cm above the ground with a hand saw DCS520 (Makita). The plants obtained from each subplot were weighed on a B15 S electronic scale (Axis, Gdańsk, Poland), rounding up the weight to 5 g. This way, the yield of fresh biomass obtained from a given unit was determined. From the fresh biomass yield and its moisture, the yield of dry biomass was calculated. The moisture content was determined with the oven-dry method. For this purpose, the biomass was dried at 105±2ºC in a Premed KBC G-65/250 dryer until solid mass was obtained (PN 80/G-04511).

Statistical Analysis

The research results were processed statistically by a two-factor ANOVA. SNK multiple test (Student Newman-Keuls), which means groups of similar values, yielded homogeneous groups at a significance level $\alpha=0.05$. Furthermore, for the analyzed properties, arithmetic means and standard variance were calculated. All the statistical analyses were conducted using STATISTICA 9.0 (StatSoft, Inc., www.statsoft.pl) software.

Results

Weather Conditions

During our entire research period (2010-11), the average air temperature during the vegetative period was higher than the multi-year average (Table 2). However, the average temperature for 2010 was 0.8ºC lower than the value measured over many years.

The total rainfall in 2010 was 14.4% higher than the average for the years 1998-2007 (Table 3). The total rainfall in the plant growing period was also almost 18% higher than the multi-year average. Extremely little rainfall, however, was recorded in April 2010 (17.1 mm). This had an adverse impact on young planted seedlings of energy crops. In the following months (May and June), rainfall exceeded the

Table 2. Average air temperature (ºC) in 2010-2011 and in the multi-year period.

Month \ Year	2010	Deviation*	2011	Deviation*	1998-2007
I	-8.9	-6.9	-1.7	0.3	-2.0
II	-3.0	-1.5	-6.0	-4.5	-1.5
III	2.4	0.8	1.9	0.3	1.6
IV	8.1	-0.1	9.8	1.6	8.2
V	12.7	-0.4	13.3	0.2	13.1
VI	16.5	0.7	17.4	1.6	15.8
VII	21.4	2.9	18.5	0.0	18.5
VIII	19.7	2.1	18.1	0.5	17.6
IX	12.6	-0.8	14.8	1.4	13.4
X	5.7	-2.5	8.8	0.6	8.2
XI	4.7	2.1	3.4	0.8	2.6
XII	-6.6	-6.1	2.2	2.7	-0.5
Period mean IV-X	13.8	0.3	14.4	0.8	13.5
Period mean I-XII	7.1	-0.8	8.4	0.5	7.9

*Deviation from the mean of the multi-year period (1998-2007).

long-term average, reaching 197% and 115% of the latter, respectively. The subsequent months of the vegetation period were again characterized by lower rainfall values. The total rainfall in the vegetative season of 2011 (447.3 mm) was actually on the same level as the average rainfall for the years 1998-2007. From the beginning of spring 2011 the rainfall was lower than in the long-term average. In March, April, and May it equalled 49%, 92%, and 81% of the multi-year average rainfall, The beginning of the second plant growing season was characterized by a rainfall level insufficient for plants beginning vegetation. In July, the rainfall was 154 mm, being double the multi-year value. In the following months, rainfall was lower than the multi-year average.

To recap, 2010 was uniform in average air temperature. Although the first two months were colder, no spring ground-frost appeared. Thus, the plants benefited from the temperatures, facilitating their growth and development. The annual volume of rainfall as well as the amounts recorded for the vegetative season only were higher than the corresponding multi-year values. However, the distribution of rainfall varied significantly, which undoubtedly curbed plant growth and development. Little rainfall in April affected assimilation of the planted green seedlings of black locust; willow and poplar cuttings endured those conditions far better, having been planted in soil that kept internal moisture, and continued growing under heavy May rainfall. In contrast, some black locust seedlings dried right after planting and did not resume vegetation when rainfalls came. The second year (2011) was generally warmer than the multi-year average, but total rainfall was on the same level. However, the distribution of rain was unfavourable.

Survivability, Biometric Features and Health of the Plants

The number of plants (2010 and 2011) and their biometric features (2010) were significantly varied only within the species. No statistically significant differences in the second factor and mutual interactions were reported. The average number of plants at the end of the first year (2010) was 9,544.8 individuals per ha, and the standard deviation was above 1,600 plants·ha^{-1} (Table 4). Among the three species, an outstanding number of willow plants survived (10,579 indiv.·ha^{-1}). Poplar performed nearly as well, but significantly fewer black locust plants managed to survive (7,662 indiv.·ha^{-1}). It can therefore be stated that an average loss of plants after the first year was 4.79% for willow, 6.46% for poplar, and 31.04% for black locust. Such a high loss of black locust plants was due to rainfall shortages in April 2010. The total number of plants after the second year (i.e. at the end of 2011) was lower than after the first year. The number of willow and poplar plants remained unchanged, but the number of black locust plants fell by over 1,000 of indiv. per ha as compared to the first year.

In the first year, significantly the highest number of shoots was recorded for willow (on average 1.69 pieces (Table 5). On the other hand, black locust produced significantly the smallest number of shoots (1.20 on average)

Table 3. Total rainfall (mm) in 2010-11 and in the multi-year period.

Month \ Year	2010	Multi-year (%)	2011	Multi-year (%)	1998-2007
I	22.5	52.3	32.1	74.7	43.0
II	18.7	56.7	56.5	171.2	33.0
III	30.6	78.5	19.1	49.0	39.0
IV	17.1	47.5	33.2	92.2	36.0
V	114.4	197.2	46.8	80.7	58.0
VI	89.9	115.3	79.5	101.9	78.0
VII	58.5	76.0	154.0	200.0	77.0
VIII	191.0	222.1	84.9	98.7	86.0
IX	30.1	56.8	18.3	34.5	53.0
X	26.2	44.4	30.6	51.9	59.0
XI	90.8	178.0	9.6	18.8	51.0
XII	62.0	140.9	24.5	55.7	44.0
Period sum IV-X	527.2	117.9	447.3	100.1	447.0
Period sum I-XII	751.8	114.4	589.1	89.7	657.0

Table 4. Number and losses of crops under consideration after the first and the second year of vegetation.

Species	Year of vegetation	Number of crops (pieces·ha^{-1})	Losses (%)
Black Locust	2010	7,662.0±1,330.7 b	31.04±11.9 a
Poplar		10,393.5±665.0 a	6.46±5.9 b
Willow		10,578.7±826.9 a	4.79±7.4 b
Mean		9,544.8±1,655.7	14.10±14.9
Black Locust	2011	6,574.1±1,337.6 b	40.83±12.0 a
Poplar		10,393.5± 665.0 a	6.46±6.0 b
Willow		10,578.7± 826.9 a	4.79±7.4 b
Mean		9,182.1±2,097.4	17.36±18.9

± standard error of the mean
a. b. c. … homogenous groups

Table 5. Biometric features after the first year of vegetation (2010).

Species	Number of shoots (pieces)	Crop height (m)	Shoot diameter (mm)
Black Locust	1.20±0.1 c	1.20±0.16 c	8.94±1.8 c
Poplar	1.51±0.2 b	1.84±0.17 b	14.96±1.5 a
Willow	1.69±0.2 a	2.34±0.20 a	13.62±2.2 b
Mean	1.47±0.3	1.79±0.50	12.51±3.2

± standard error of the mean
a. b. c. … homogenous groups

with significantly more secondary or even tertiary branches. In the experiment, the average height of plants at the end of the first vegetative season was 1.79 m and the standard deviation value was 0.5. The willow plants were significantly the highest (up to 2.34 m). The poplar plants were on average 0.5 m lower, but significantly the shortest plants were produced by black locust. The poplar plants had significantly the thickest shoots, with an average diameter being 14.96 mm.

Table 6 presents the significance of major effects and first order interaction in the second year of vegetation. A significantly largest number of shoots was recorded for black locust, with an average of 1.98 shoots (Table 7). The number of black locust shoots rose in 2011 compared to 2010 due to some damage caused by animals during winter, which made the plants generate new shoots. Furthermore, black locust grew far more secondary and tertiary branches. The number of shoots from each willow rootstock was similar to the number of black locust shoots. A significantly smaller number of shoots per rootstock was grown by poplar. The number of shoots per rootstock was significantly negatively co-related with the plants' growing density, height, and shoot diameter (Table 8).

In the experiment, the height of plants after the second growing season reached an average of 3.57 m (Table 7). Among the three species, willow was significantly the highest (4.30 m). For the control, the height was 4.02 m and in the other variants, where lignin, micorysis, and fertilization were applied, the height reached 4.83 m. The poplar plants were slightly shorter than the willow ones (4.22 m on average). Of the three species, the shortest plants were grown by black locust. By analyzing the height of plants from all treatments, it was demonstrated that significantly the highest plants (on average 3.88 m) grew on plots where lignin, micorysis, and fertilization had been applied. The shortest plants, on the other hand, were recorded for the control treatment, with an average height of 3.29 m. The average height of plants in the remaining treatments was contained in one intermediate homogenous group with the height of plants being significantly positively correlated to the shoot diameter (Table 8).

The significantly largest diameter of shoots was recorded in the case of poplar (31.33 mm); the corresponding value for willow was significantly lower (26.57 mm; Table 7). As for black locust, the shoot diameter was the thinnest, due to the reasons mentioned previously. Poplar grew the thickest shoots in the treatment where lignin and mineral fertilization were applied and willow – in the treatment with lignin, micorysis, and fertilization. The analysis of the diameter of shoots from all the treatments evidenced that significantly the thickest shoots (on average of 27.37 mm) were grown in the treatment where lignin and fertilization were applied. The thinnest shoots, on the other hand, were grown in the variant treated with micorysis alone.

In the vegetative seasons in 2010 and 2011, plants of the three species were not infested by pathogens. Thus, no adverse impact on the growth and development of the plants by diseases or pests was observed. Willow, poplar, and black locust leaves had intense, natural green coloration until the end of the growing season of 2010. In mid-October, after autumn ground-frost, leaves of black locust

Table 6. Significance of major effects and primary interactions after the second year of vegetation.

Specification	Number of shoots	Crop height	Shoot diameter	Yield of fresh biomass	Yield of dry biomass
Species	**	**	**	**	**
Soil enrichment procedure	NS	**	**	**	**
Species × Soil enrichment procedure	NS	NS	NS	NS	NS

**$p < 0.01$; NS = not significant

Table 7. Biometric features of crops after the second year of vegetation (2011).

Species	Soil enrichment procedure	Number of shoots (pieces)	Crop height (m)	Shoot diameter (mm)
Black Locust	C	1.97±0.4	1.98±0.49	15.67±4.2
	L	1.67±0.2	2.22±0.30	16.57±3.2
	F	2.23±0.3	1.74±0.20	14.67±0.7
	L + F	2.07±0.1	2.44±0.09	19.00±3.2
	M	2.23±0.3	2.01±0.48	14.13±1.5
	M + F	2.20±0.5	2.35±0.30	16.37±0.4
	L + M	1.83±0.5	2.30±0.35	17.73±4.0
	L + M + F	1.67±0.2	2.43±0.21	19.47±1.8
Mean		1.98 ±0.4 a	2.18 ±0.36 b	16.70 ±2.9 c
Poplar	C	1.30±0.2	3.88±0.04	28.80±1.2
	L	1.50±0.3	4.08±0.52	30.27±5.3
	F	1.53±0.2	4.33±0.38	32.40±1.0
	L + F	1.43±0.2	4.70±0.12	35.77±2.7
	M	1.43±0.3	4.04±0.12	28.90±1.2
	M + F	1.37±0.3	4.32±0.48	33.17±3.2
	L + M	1.40±0.1	4.00±0.13	29.13±1.1
	L + M + F	1.50±0.2	4.39±0.34	32.17±2.7
Mean		1.43±0.2 b	4.22 ±0.37 a	31.33±3.3 a
Willow	C	1.57±0.2	4.02±0.57	24.13±3.6
	L	1.67±0.3	4.19±0.50	26.73±3.9
	F	1.83±0.1	4.05±0.24	26.37±2.9
	L + F	1.93±0.4	4.19±0.38	27.33±1.5
	M	1.80±0.5	4.20±0.26	22.67±2.6
	M + F	2.03±0.6	4.34±0.32	28.47±5.4
	L + M	1.83±0.1	4.58±0.62	27.23±5.9
	L + M + F	2.03±0.3	4.83±0.15	29.60±1.7
Mean		1.84 ±0.3 a	4.30 ±0.43 a	26.57 ±3.8 b
Mean	C	1.61±0.4	3.29 ±1.06 b	22.87±6.4 bc
	L	1.61±0.2	3.50±1.03 ab	24.52±7.1 b
	F	1.87±0.4	3.37±1.26 ab	24.48±8.0 b
	L + F	1.81±0.4	3.78±1.04 ab	27.37±7.6 a
	M	1.82±0.5	3.42±1.10 ab	21.90±6.6 c
	M + F	1.87±0.6	3.67±1.04 ab	26.00±8.1 b
	L + M	1.69±0.3	3.63±1.09 ab	24.70±6.4 b
	L + M + F	1.73±0.3	3.88±1.13 a	27.08±6.1 ab
Mean		1.75±0.4	3.57±1.06	24.86±7.0

± standard error of the mean

a. b. c. … homogenous groups

dried, while willow and poplar leaves turned partly black, although they did not dry and remained partly green until the end of October. In mid-October 2011, after autumn ground-frost, poplar leaves that had partly changed their colour into black were the first to fall. Furthermore, it should be added that in winter 2011 black locust plants were browsed by some wild animals, mainly deer and hare. As mentioned above, the loss of black locust plants increased by about 10% versus the first vegetation period. The reason could have been both partial freezing as well as the grazing of young shoots by wild animals. It may be concluded that prospective black locust plantations should be fenced in order to prevent damage caused by wild animals. In the present experiment, the plantation was fenced with forest mesh, which turned out to be effective protection against wild animals.

Crop Yield

The crop yields varied significantly between the species and in relation to the soil enrichment regimes. No statistically significant differences were reported with respect to interactions between the experimental factors (Table 6). After two years of cultivation, the yield of fresh willow was the highest, reaching on average of 20.87 $Mg{\cdot}ha^{-1}$ (Table 9). The yields recorded for poplar and willow were the same, but black locust gave five-fold smaller yield. Among the soil enrichment regimes, the treatments with lignin and fertilization, micorysis, and fertilization, as well as lignin with fertilization and micorysis, provided the highest, identical yields of fresh lignocellulosic biomass. The second homogeneous group included the treatment where only fertilization was applied. The remaining three treatments (the control, lignin, and micorysis amendments) constituted the third homogenous group. The crop yield was significantly positively correlated to the height, shoot diameter, and number of plants; in contrast, it was negatively correlated to the number of shoots per plant (Table 8).

The average dry matter yield of willow after two years of cultivation was 10.17 $Mg{\cdot}ha^{-1}$; for poplar it was about 8% lower, but for black locust was as low as 2.28 $Mg{\cdot}ha^{-1}$ (Table 9). The yield of dry biomass from the three species was 5.09, 4.67, and 1.14 $Mg{\cdot}ha^{-1}{\cdot}year^{-1}$, respectively. Among the soil enrichment regimes, the highest yield of dry matter was obtained for the treatment where fertilization with micorysis was applied (4.22 $Mg{\cdot}ha^{-1}{\cdot}year^{-1}$). The same level of yield was obtained from the plants cultivated in the treatments amended with lignin and fertilization or with lignin, fertilization, and micorysis. In the treatment where only fertilization was applied, the yield was about 8.6% lower than in the most efficient treatment. The last dry matter yield homogenous group included the treatments with lignin, micorysis, lignin + micorysis, and the control treatments. In the two latter treatments the yields were on average almost 38% lower than in the treatment where micorysis with fertilization was applied. Throughout the whole experiment, the yield recorded for poplar was the highest in the treatment with lignin and fertilization (6.47 $Mg{\cdot}ha^{-1}{\cdot}year^{-1}$ d.m.), but the yield for willow was the high-

Table 8. Co-relation Coefficient r – Pearson for a selection of features.

Specification	Number of crops	Number of shoots	Crop height	Shoot diameter	Yield of fresh biomass	Yield of dry biomass
Number of crops	1.00	-0.36*	0.82*	0.69*	0.78*	0.77*
Number of shoots	-0.36*	1.00	-0.35*	-0.44*	-0.27*	-0.24*
Crop height	0.82*	-0.35*	1.00	0.90*	0.87*	0.86*
Shoot diameter	0.69*	-0.44*	0.90*	1.00	0.82*	0.80*
Yield of fresh biomass	0.78*	-0.27*	0.87*	0.82*	1.00	1.00*
Yield of dry biomass	0.77*	-0.24*	0.86*	0.80*	1.00*	1.00

*Co-relation co-efficients significant for $p \leq 0.05$ with $n = 72$

est when it was cultivated in the treatment with lignin, fertilization, and micorysis (6.38 $Mg \cdot ha^{-1} \cdot year^{-1}$ d.m.).

Discussion

In Poland, willow is the most widespread SRWC, grown on 6,200 ha, whereas poplar is estimated to be cultivated on approximately 650 ha [27]. Black locust as an SRWC is grown only on small-size experimental fields. Recently, poplar has been gaining interest in Poland, mainly because large cellulose-processing plants demand this species for paper production and energy generation purposes. For instance, the International Paper Company in Kwidzyn together with Green Wood Resources intend to plant poplar over 10,000 ha and eventually expand the cultivation area to 25,000 ha [28]. As a result, the largest European poplar plantation may soon be set up in Poland, namely near Kwidzyn (in the Province of Pomerania). At the moment, farmers willing to start plantations or lease land under such plantations are being sought. Under a pilot program, a poplar plantation has already been established within the SRWC system on an area of over 1,000 ha. In other countries, poplar, used as an energy and industrial crop gains in popularity as well. Spinelli et al. [29] state that woody crops in short rotations cultivated on arable land, especially poplar, has recently become very popular in Italy, already covering more than 4,000 ha. In Greece, poplar plantations, mainly traditional ones, occupy 16,100 ha [7]. However, the largest acreage of poplar plantations, grown mainly for paper production and only partly as an energy crop, is in Spain. In 2008 approximately 135,700 ha were dedicated to this species [30]. On the other hand, in Sweden the acreage under willow in the SRWC system is approximately 13,000 ha [31]. Hungary, in turn, has the largest acreage of black locust woodland, i.e. 400,000 ha. As a result, attempts are made there to produce biomass from this species in short rotations [9, 32]. According to AEBIOM [31], in 2008 the area occupied by willow and poplar plantations in the EU ranged from 25,500-32,500 ha and 6,600-7,300 ha, respectively.

The key issue is the yield of the above plant species, which depends on climatic conditions, soil quality, cultivated species and their variety, agricultural technology, planting density and, in the case of willow, poplar and black locust, on the harvesting cycle. In Poland, the yield of willow is most thoroughly recognized, but it is highly variable and obtained from numerous species and varieties. In experiments and under optimal conditions, the willow yield was several times higher than in the present research. The yield from commercial plantations was noticeably lower than in experiments, and in the case of large plantations (70-300 ha) run by the University for Warmia and Mazury it reached 4 to 10 $Mg \cdot ha^{-1} \cdot year^{-1}$ d.m. on average [33-34]. In Sweden, similar yields are recorded because of the high yield of willow biomass on experimental plantations that could not be achieved on commercial plantations [35]. This dependence is confirmed by the figures obtained from over 1,500 plantations, where the average willow yield was as low as 2.67 $Mg \cdot ha^{-1} \cdot year^{-1}$ at the maximum value of 20.54 $Mg \cdot ha^{-1} \cdot year^{-1}$ [36].

On the other hand, the yield from poplar plantations cultivated in short rotation on arable land in Poland is underestimated. It is reported that on well-managed plantations and on good quality soil, the yield may reach over eight tons of d.m. per ha per year of maintaining the plantation [8]. The yield obtained in the present experiment was lower. Considerably higher yields from poplar plantations are achieved in Italy [37]. *Populus deltoides* L. clone in two-year rotation gave the yield of 11.7 $Mg \cdot ha^{-1} \cdot year^{-1}$ d.m. Furthermore, the extension of rotation to three or four years influences the yield of poplar. Other authors claim that seven clones of *Populus* × *canadensis* poplar and seven clones of *Populus deltoides* poplar cultivated in Italy did not give such high yield [14]. At a density of 10,000 poplar $plants \cdot ha^{-1}$, after nine years of cultivation and four rotations, the average of 49% of plants survived. The average biomass yield of a clone of *Populus deltoides* species for a period of nine years of cultivation was 9.7 $Mg \cdot ha^{-1} \cdot year^{-1}$ d.m. and the yield from clones of *Populus* × *canadensis* species was lower, i.e. 5.6 $Mg \cdot ha^{-1} \cdot year^{-1}$ d.m. Comparative analysis indicated that the average yield of 14 poplar clones was 8.34 $Mg \cdot ha^{-1} \cdot year^{-1}$ d.m., and that of six willow clones was higher (12.10 $Mg \cdot ha^{-1} \cdot year^{-1}$ d.m.). Other sources state that the yield of poplar was greatly varied (1.6-28 $Mg \cdot ha^{-1} \cdot year^{-1}$ d.m.), depending on climatic conditions, soil, species and clone types, harvesting rotations, age of plantation, fertilization intensity, and other agricultural techniques [38-41].

Table 9. Crop yield after the second year of vegetation.

Species	Soil enrichment procedure	Yield of fresh biomass ($Mg \cdot ha^{-1}$)	Yield of dry biomass ($Mg \cdot ha^{-1}$)	Yield of dry biomass ($Mg \cdot ha^{-1} \cdot year^{-1}$)
Black Locust	C	4.16±1.45	2.17±0.78	1.08±0.39
	L	4.42±1.39	2.37±0.75	1.19±0.37
	F	3.76±1.20	1.95±0.62	0.97±0.31
	L + F	6.07±2.70	3.20±1.42	1.60±0.71
	M	4.86±2.23	2.59±1.13	1.29±0.56
	M + F	3.13±1.00	1.65±0.52	0.82±0.26
	L + M	4.00±3.05	2.14±1.24	1.07±0.62
	L + M + F	4.12±1.28	2.18±0.68	1.09±0.34
Mean		4.32±2.28 b	2.28±1.21 b	1.14±0.60 b
Poplar	C	17.32±0.77	8.08±0.35	4.04 ±0.17
	L	19.84±3.15	9.21±1.56	4.60±0.78
	F	20.01±4.36	9.11±1.97	4.55±0.99
	L + F	28.19±7.09	12.94±3.16	6.47±1.58
	M	17.74±5.73	8.32±2.68	4.16±1.34
	M + F	24.79±4.70	11.47±2.25	5.73±1.12
	L + M	13.13±0.93	6.13±0.45	3.06±0.22
	L + M + F	20.52±6.41	9.50±2.99	4.75±1.50
Mean		20.19±5.90 a	9.34±2.70 a	4.67±1.35 a
Willow	C	16.26±2.89	8.12±1.58	4.06±1.30
	L	18.56±3.93	8.95±2.28	4.47±1.14
	F	24.78±8.05	12.25±4.00	6.13±1.98
	L + F	18.04±3.31	8.82±2.21	4.41±1.11
	M	15.56±1.35	7.47±0.66	3.74±0.33
	M + F	25.04±4.45	12.21±2.19	6.10±1.10
	L + M	22.48±6.87	10.80±3.41	5.40±1.71
	L + M + F	26.27±2.36	12.77±1.24	6.38±0.62
Mean		20.87±6.90 a	10.17±3.36 a	5.09±1.68 a
Mean	C	12.58±6.85 b	6.12±3.27 b	3.06±1.64 b
	L	14.27±7.82 b	6.84±3.65 b	3.42±1.83 b
	F	16.18±8.01 ab	7.77±3.84 ab	3.88±1.92 ab
	L + F	17.43±7.12 a	8.32±3.56 a	4.16±1.78 a
	M	12.72±4.85 b	6.13±2.87 b	3.06±1.44 b
	M + F	17.65±8.48 a	8.44±4.35 a	4.22±2.17 a
	L + M	13.20±6.48 b	6.35±3.33 b	3.18±1.67 b
	L + M + F	16.97±7.48 a	8.15±3.64 a	4.08±1.82 a
Mean		15.13±8.37	7.27 ±3.98	3.63±1.99

± standard error of the mean
a. b. c. … homogenous groups

Black locust (*Robinia pseudoacacia* L.) belongs to the Fabaceae family, so the roots of this species are in a symbiotic relationship with *Rhizobium* bacteria, which fix atmospheric nitrogen. This species is therefore very important for rehabilitation and conservation of the poorest soil, spoil tips, eroded slopes and, potentially, as a species used in field plantations for biomass production on poor soil. For instance, in central Hungary black locust plantations for energy purposes were established on poor sand soil using native black locust as well as a range of new varieties [32]. In comparison to the authors' research-based experience, black locust yield obtained in a longer rotation (five-year rotation) was higher (4.1-4.5 m), and the shoot diameter was 2.8-3.5 cm. At a density of about 22,000 of plants·ha^{-1}, the annual growth of dry matter was 6.5 Mg·ha^{-1}·year^{-1}. In the case of two lower densities (approximately 13 and 6,600 plants·ha^{-1}), the yields were 33% and 51% lower. It was reported that for the lowest density, in five-year rotation, the highest yield was given by the variety Üllöi (8.0 Mg·ha^{-1}·year^{-1}), followed by Jászkiséri (7.4 Mg·ha^{-1}·year^{-1}) and the native black locust (6.7 Mg·ha^{-1}·year^{-1}). In seven-year rotation, the yield was on average 1 Mg·ha^{-1} higher than in five-year rotation.

On the other hand, in Germany Gruenewald et al. [42] conducted research on black locust planted on poor soil restored from a former open-pit coal mine. Black locust was planted at a density of about 12,100-14,800 plants·ha^{-1} and harvested in three- and six-year rotations. The yield of black locust in the three-year rotation was on average 4 Mg·ha^{-1}·year^{-1} d.m. and in the six-year rotation it was 6 Mg·ha^{-1}·year^{-1} d.m. These authors concluded that their results were comparable to other figures available in literature, where cited yields ranged from 3.3 to 8 t d.m.·ha^{-1}·year^{-1} [43-45]. It is highlighted that despite the low quality of soil and adverse weather conditions, yields of black locust are the highest. Furthermore, the research results explicitly indicated that black locust adapts well to poor sandy soils with low nutrient content. On the other hand, Geyer [46] states that at a very high density of black locust planting (111,000 plants·ha^{-1}) and annual harvesting in the first rotation, the yield was 6.5 Mg·ha^{-1}·year^{-1} d.m. In the consecutive two years, the yield rose by 80% and in the sixth year it approximated the first year's yield. Unfortunately, with such a high density of plants in the first stage, only 17% of crops survived until the sixth year.

Conclusions

This paper is among the earliest attempts at evaluating the yield of three species of SRWC grown in two-year rotations in northeastern Poland, on soil sub-standard for food or fodder crops. After two plant growing seasons, significantly the highest yield was recorded for willow. Poplar plants grew to a similar height and produced the shoots of the biggest diameter. Significant variation of yields of the three plant species was reported. In a two-year rotation cycle of harvesting, the willow and poplar yields were much higher than the yield of black locust, despite the fact that the crops were cultivated on soil with low nutrient content.

The applied soil enrichment regimes significantly increased the yield. The research results also indicate that plantations of black locust should be fenced in in order to protect the crop against wild animals. Willow and poplar crops were not browsed by animals.

Notably, the research results should be referred to the corresponding climatic and soil conditions as well as agricultural techniques under which the experiment was conducted. As has been proven empirically and indicated in the literature, the three species may produce different yields depending on the type of soil, weather conditions, and agricultural techniques. The present research demonstrates that it is possible to improve SRWC yield on poor soil, unsuitable for food and fodder crops. Furthermore, the research results indicate the need to continue studies on SRWC in order to propose recommendations about species, varieties or clones suitable for given soil conditions as well as adequate agricultural techniques, since it has been proven that these factors significantly influence the yield. The research must be verified in subsequent harvesting cycles of different cutting frequency. This is an essential step as this factor directly influences the energy savings, economic efficiency, and environmental impact of the production and use of lignocellulosic biomass for energy or industrial purposes, which will be a subject for further research.

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