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Original Research

Short Rotation Woody Crops Grown on Marginal Soil for Biomass Energy

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Abstract

Short rotation woody crops are grown to be used as feedstock for energy and industrial purposes in many countries of Europe, and in the USA and Canada. Wood biomass is acquired from forests, the wood industry, and as a by-product of trimming trees and bushes. In future, considerable amounts of wood biomass should be supplied by dedicated energy crops (willow, poplar, black locust). The aim of this study was to determine the morphological features, yield and energy value of the yield of three species of plants grown at a site with poor soil quality and low usability for edible crops. The study has shown that the species of willow and poplar can be grown on poor quality agricultural land because they provide high yield, high energy, and high coal equivalent. However, the biomass of black locust may fail to provide sufficient yield to justify setting up a plantation using this species.

Keywords: biomass, willow, poplar, black locust, yield, yield energy value, coal equivalent

Introduction

Short rotation woody crops (SRWC) are grown to be used as feedstock for energy and industrial purposes in many countries of Europe, but also in the USA and Canada [1-5]. Willow is more frequently grown in northern Europe and poplar in the south. The majority of poplar trees as feedstock for paper production and, partly, for energy, are grown in Spain [6]. Poplar is also valued as feedstock for the power industry and other industries in Italy and Greece [7, 8]. Hungary has the largest areas of black locust forests, and attempts also have been made to grow it as a short-rotation crop for biomass production [9, 10]. The greatest area of willow grown in the SRWC system is in Sweden (13 thousand ha). The area of willow plantations in the entire EU is estimated at between 25,500 and 32,500 ha [3]. SRWC plantations in Poland are dominated by willow (6,200 ha) and it is estimated that poplar is grown on an area of about 650 ha [11]. Although there has been increased interest in poplar as feedstock for the paper and energy purposes in recent years for large cellulose-producing plants in Poland [12], black locust has been grown in the SRWC system only in small-area experimental plantations.

Biomass accounts for the majority of renewable energy sources worldwide, in the EU and in Poland [13]. It can be used for the production of heat, electricity, or liquid biofuels [14]. In Poland, biomass is used to generate heat in both small household installations [15, 16] and in large facilities producing heat and power [17]. Large power plants in Poland are interested in using biomass for co-combustion in the process of power generation mainly due to considerable financial support. It has been reported that 51 out of 55

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Polish power plants are licensed to generate energy in the process of co-combustion [18]. This has resulted in high consumption of biomass, which amounted to 8.4 million tons in power generation in 2011, 5.1 million tons of which was used in co-combustion. It is currently a challenge to supply such large amounts of biomass. Wood biomass is acquired from forests, the wood industry, and as a by-product in trimming trees and bushes. In future, considerable amounts of wood biomass should be supplied by dedicated plantations of SRWC (willow, poplar, black locust). Such plantations should be set up on soils with low usability for growing edible crops. Therefore, the aim of this study was to determine the survivability, morphological features, and yield of three species of plants grown at a site with poor soil quality and low usability for edible crops, depending on the method of soil enrichment. Another was to determine the biomass yield energy value and its coal equivalent.

Materials and Methods

Field Experiment

This study was based on a two-factorial strict experiment, set up in late April 2010 at the Research and Didactic Station in Łężany, owned by the University of Warmia and Mazury in Olsztyn.

Three plant species: willow, poplar, and black locust, were the first experiment factor. Willow *Salix viminalis*, clone UWM 006 originated from the collection of Department of Plant Breeding and Seed Production of the University of Warmia and Mazury in Olsztyn. Poplar *Populus nigra* × *P. Maximowiczii* Henry cv. Max-5 was provided by a farm in northern Austria. Black locust (*Robinia pseudoacacia*) was provided by a forest nursery in Poland. The crops were planted at a density of 11,1100 per ha. The experimental plot was divided into three subplots, 18.0 m^2 each.

The other experimental factor was a method of soil enrichment, referred to as "fertilization." The following options were identified: lignin (L), mineral fertilization (F), mycorrhiza inoculation (M), lignin+mineral fertilization (L+F), mycorrhiza+mineral fertilization (M+F), lignin+ mycorrhiza (L+M); lignin+mycorrhiza+mineral fertilization (L+M+F), and a control site with no soil enrichment (C).

Lignin (L), a by-product of paper production, was applied in a dose of 13.3 $Mg \cdot ha^{-1}$ in the spring preceding the experiment. 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. Mycorrhiza inoculation (M) was applied separately for each of the species between 1 and 10 of September 2010, when the willow, poplar, and black locust crops had been sufficiently well rooted. Liquid vaccination of 30-35 cm^3 was applied underneath each of the crops using a hand-operated instrument. In the first year, no mineral fertilization (F) 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 a 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 of June 2011.

Detailed information on setting up and conducting the experiment is provided by Stolarski et al. [19]. This study presents the findings of a three-year study of plant vegetation.

Soil Characteristics

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 and enriched soil Bv horizons, whereas the native rock C layer contained loose sand. The content of clay particles in the particular soil horizons did not exceed 2%. The characteristics of the site where the experiment was set up were presented in the paper by Stolarski et al. [19]. The soil conditions were evaluated after three vegetation periods at the control sites and at ones where lignin, mycorrhiza, and mineral fertilization was used. Basic soil samples were taken from each experimental site using soil sampler. Basic soil samples were combined into general soil samples and analyzed in laboratory (according to PN-R-04031). The evaluation took into account the soil pH in H_2O and in 1 $mol \cdot dm^{-3}$ KCl (potentiometrically), the content of available phosphorus, potassium (Egner-Riehm method), and magnesium (Schachtschabel method). Moreover, hydrolytic acidity (Hh) and total alkaline cations (S) (Kappen method) were determined at the control site and at one where lignin was used. These data were used to calculate the total soil sorption capacity (T=Hh+S) and the sorption complex saturation with alkalis (S/T). Total organic carbon (Tiurin method) and total nitrogen (Kjeldahl method) was determined at the lignin site, which enabled us to determine the C:N ratio.

Weather Conditions

It was found that the years 2010-12 (in which the experiment was conducted) were close to the multi-year period 1998-2007 (Fig. 1) in terms of the air temperatures throughout the experimental period. The largest temperature differences between individual years were recorded in the winter. The average air temperatures in individual vegetation periods were similar. The warmest vegetation period was in 2011 (14.4ºC) and the coldest was in 2012 (13.5ºC). The hottest month of the vegetation period was July, when the average air temperature ranged from 18.5ºC in 2011 to 21.4ºC in 2010. October was the coldest month of the vegetation period and February was the coldest month of the year.

The rainfall in 2010-12 varied compared to its values from the multi-year period. The rainfall in 2011 was lower by 68 mm than the rainfall in the multi-year period, whereas in 2010 and 2012 it was higher by 95 and 138 mm, respectively. The rainfall in each of the 2010-12 vegetation periods was higher than at the same time in the multi-year period, but its distribution varied significantly. The rainfall in April in 2010 and 2011 was lower than at a similar time during the multi-year period, which undoubtedly may have restricted the initial growth of plants, especially in the year when the experiment was established (2010). Low rainfall in April 2010 had a particularly negative effect on how well the seedlings of black locust took root. On the other hand, the willow and poplar cuttings fared much better in those conditions. This was a consequence of the fact that the cuttings placed in the soil retained their internal moisture and continued their vegetation after the intensive rainfall of May, whereas some black locust seedlings dried out after being planted and did not resume their vegetation despite the rain. No additional plant watering was done in the experiment in order to verify the feasibility of setting up a plantation that modelled the potential conditions of running a commercial plantation.

Biometric Measurements, Determination of Biomass Yield, and Its Energy Value

After the third period of vegetation (2012), the plant density on each plot, converted to the area of 1 ha, was determined in early December. Moreover, the number of stems on a plant was counted, taking into account live stems longer than 1.5 m. Biometric measurements were performed on 10 plants at every site; the following were measured: plant height, stem diameter (measurements were made 0.5 m above the ground level). The plant yield was determined by cutting down the entire plants with a DCS520 (Makita) chain saw 5-10 cm above the ground level. Plants obtained from every site were weighed with B15 S scales (manufactured by Axis, Gdańsk, Poland) within an accuracy of 5 g, which gave the fresh biomass yield from a site. The fresh biomass yield and its moisture content were used to calculate the dry matter biomass yield at each site. The lower heating value of fresh biomass ($GJ \cdot Mg^{-1}$) and its yield ($Mg \cdot ha^{-1}$) were taken to calculate the yield energy value ($GJ \cdot ha^{-1}$). Furthermore, the yield energy value was expressed as coal equivalent, assuming that 1 Mg of medium quality hard coal has a lower heating value of 25 GJ.

Statistical Analysis

The results were worked out statistically with a two-way analysis of variance (ANOVA). Homogeneous groups at the level of significance of $\alpha = 0.01$ were identified with the multiple SNK (Student Newman-Keuls) test, connecting means with a similar value. Moreover, arithmetic mean and standard deviation were calculated for each of the analyzed features. All the statistical analyses were conducted with the STATISTICA 9.0 (StatSoft, Inc.) software package.

Results

Soil Changes

The analyses of soil revealed a higher content of available forms of macronutrients at the majority of sites where lignin, mycorrhiza, and mineral fertilization were used, compared to the control sites (Table 1). The content of P_2O_5 at the sites where the soil was enriched ranged from 23.9 $mg \cdot 100 g^{-1}$ of soil for willow where lignin was used, to 37.0 $mg \cdot 100 g^{-1}$ of soil with black locust and mineral fertiliza-

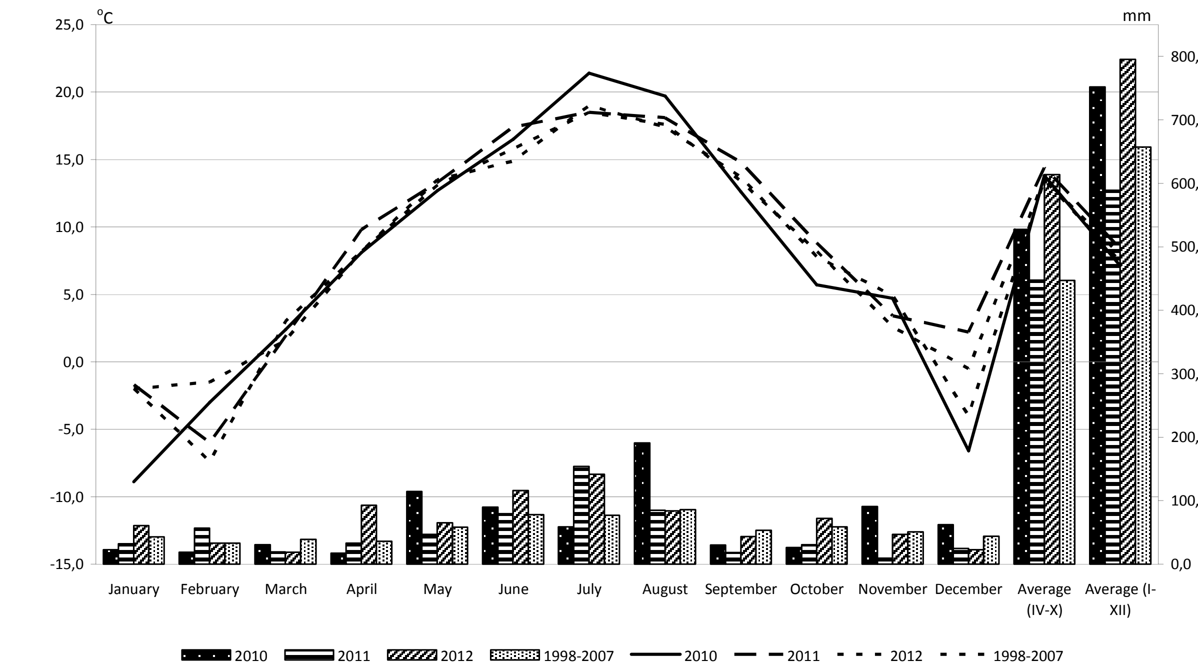

Fig. 1. Weather conditions during the 2010-12 experiment period and multi-year period 1998-2007; bars represent participation; curves represent air temperatures.

Table 1. The pH and macronutrient available forms in the soil humus layer at the examined sites.

Specification	Horizon (cm)	pH_{H2O}	pH_{KCl}	P_2O_5	K_2O	Mg
				mg·100 g^{-1} soil		
Black locust L	0-25	7.52	7.05	34.4	11.8	5.6
Black locust C	0-25	6.78	6.13	19.2	16.5	7.6
Black locust M	0-25	7.56	7.03	31.3	12.5	7.4
Black locust F	0-25	7.99	7.42	37.0	13.8	13.3
Willow L	0-25	6.94	6.30	23.9	17.5	9.7
Willow C	0-25	6.78	6.09	21.1	16.1	7.6
Willow M	0-25	7.51	6.97	33.0	17.0	12.9
Willow F	0-25	7.51	6.98	33.0	17.7	9.1
Poplar L	0-25	7.32	6.85	27.0	16.0	5.7
Poplar C	0-25	7.14	6.68	24.2	15.5	6.5
Poplar M	0-25	7.55	6.78	33.2	16.8	14.9
Poplar F	0-25	6.94	6.15	33.4	20.4	10.4

Table 2. The soil humus layer characteristics at the examined sites.

Specification	Horizon (cm)	Hh	S	T	S/T	Organic carbon	N-total	C:N
		mmol·(+) 100 g^{-1} soil				%		
Black locust L	0-25	0.65	24.10	24.75	97.4	1.31	0.080	16.4
Black locust C	0-25	1.34	10.90	12.24	89.1	1.13	0.093	12.2
Willow L	0-25	1.55	12.50	14.05	89.0	1.50	0.100	15.0
Willow C	0-25	1.23	10.80	12.03	89.8	1.29	0.092	14.0
Poplar L	0-25	0.78	18.70	19.48	96.0	1.25	0.085	14.7
Poplar C	0-25	0.93	14.30	15.23	93.9	1.16	0.082	14.1

Hh – hydrolytic acidity, S – total alkaline cations, T – total soil sorption capacity, S/T – the sorption complex saturation with alkalis.

tion. On the other hand, P_2O_5 content at control sites was lower and did not exceed 24.2 mg·100 g^{-1} of soil. The content of available K_2O species was higher at sites with enriched soil compared to the control, except at the black locust site, where the opposite effect was observed. The content of available magnesium lay within the range from 5.6 to 14.9 mg·100 g^{-1} of soil. Its lowest content was found at sites with black locust and poplar, at which lignin was used (5.6-5.7 mg·100 g^{-1} soil). The use of mycorrhiza for willow and poplar resulted in an increase in magnesium content at those sites (12.9-14.9 mg·100 g^{-1} of soil) rather than at other sites with these plants. The soil pH varied from site to site. It was slightly acidic or neutral, and alkaline at the black locust site with mineral fertilization. The value of pH_{KCl} ranged from 6.09 to 7.42. The pH value was usually the lowest at the control sites (pH_{KCl} = 6.09-6.68), except at the poplar site with mineral fertilization (Table 1).

The use of lignin had a positive effect on the total organic carbon content and the sorption properties (Table 2). The total sorption capacity (T), which indicates the soil capability of retaining nutrients, was the highest at the black locust site (24.75 mmol(+)·100 g^{-1} of soil). It was more than twice lower at the control site for the same plant species. Saturation of the sorption complex with alkaline cations (S/T) at all the sites was about 90% or more. The total organic carbon content at the sites with lignin was higher at all sites than at the control site. It was the highest at the willow site with lignin (1.50%), and was the lowest at the black locust control site (1.13%). A slightly broader C:N ratio at the sites where lignin was used (14.7-16.4) compared to control (12.2-14.1) is a result of the content of C and lack of N in lignin.

Survivability, Biometric Features, and Health Conditions of the Plants

The number of plants after the third vegetation year varied significantly only within species. No significant differ-

Table 3. Significance of major effects and primary interactions after the third year of vegetation.

Specification	Number of plants	Number of stems	Plant height	Stem diameter	Yield of fresh biomass	Yield of dry biomass	Yield energy value	Coal equivalent
Species	**	**	**	**	**	**	**	**
Soil enrichment procedure	NS	NS	**	**	**	**	**	**
Species × Soil enrichment procedure	NS	NS	NS	NS	NS	NS	NS	NS

**p < 0.01; NS – not significant

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

Species	Soil enrichment procedure	Number of plants (pieces·ha^{-1})	Losses (%)
Black locust	C	5555.6±962.3	50.0±8.7
	L	6481.5±2103.3	41.7±18.9
	F	6296.3±1156.5	43.3±10.4
	L+F	7777.8±555.6	30.0±5.0
	M	6666.7±1469.9	40.0±13.2
	M+F	6111.1±962.3	45.0±8.7
	L+M	5370.4±1156.5	51.7±10.4
	L+M+F	6481.5±1398.1	41.7±12.6
Mean		6342.6±1289.1 b	42.9±11.6
Poplar	C	10555.6±0.0	5.0±0.0
	L	10185.2±1156.5	8.3±10.4
	F	10185.2±320.8	8.3±2.9
	L+F	10740.7±641.5	3.3±5.8
	M	10740.7±320.8	3.3±2.9
	M+F	10185.2±1156.5	8.3±10.4
	L+M	9629.6±848.6	13.3±7.6
	L+M+F	10000.0±555.6	10.0±5.0
Mean		10277.8±714.1 a	7.5±6.4
Willow	C	9814.8±1785.9	11.7±16.1
	L	10185.2±848.6	8.3±7.6
	F	10925.9±320.8	1.7±2.9
	L+F	10000.0±962.3	10.0±8.7
	M	10555.6±555.6	5.0±5.0
	M+F	11111.1±0.0	0.0±0.0
	L+M	10925.9±320.8	1.7±2.9
	L+M+F	10740.7±320.8	3.3±2.9
Mean		10532.4±826.9 a	5.2±7.4
Mean	C	8642.0±2547.6	22.2±22.9
	L	8950.6±2247.2	19.4±20.2
	F	9135.8±2241.4	17.8±20.2
	L+F	9506.2±1481.5	14.4±13.3
	M	9321.0±2147.7	16.1±19.3
	M+F	9135.8±2423.4	17.8±21.8
	L+M	8642.0±2622.2	22.2±23.6
	L+M+F	9074.1±2115.5	18.3±19.0
Mean		9050.9±2157.6	18.5±19.4

± standard deviation
a. b. c. … homogenous groups

ences were found for the other factor and in interactions between them (Table 3). The average number of plants after three years of vegetation was smaller than after the first and second years, and it was 9,050.9 plants·ha^{-1} (Table 4). Of the species under study, the largest number of willow plants survived (10,532 per ha). A similar number of plants was found for poplar. The number of willows and poplars was smaller by 46 and 115 per ha than after the second year of vegetation. The significantly smallest number of surviving plants was found for black locust (6,342.6 per ha). Compared to the second year of vegetation, the number of black locusts decreased by about 231 per ha. Therefore, the largest loss after the third year of vegetation was found for black locust (42.9%); it was 7.5% for poplar and 5.2% for willow. The loss of willows after the third year of vegetation ranged from 0% to 11.7% at the mycorrhiza and fertilization site and for the control site, respectively. The loss for poplar ranged from 3.3% to 13.3%. The loss of black locusts ranged from 30.0% to 51.7% at the lignin and fertilization site and for the lignin and mycorrhiza site, respectively. Compared to the second year of vegetation, the loss of black locusts increased by about 2%. No significant differences were found in terms of the number of plants between the fertilization sites, although this feature ranged from 8,642 to 9,506 per ha.

The average number of stems per stump was 1.5 (Table 5). The significantly largest number of stems was found in black locust – 1.6 on average. The number of stems on a stump in willow was similar to that in black locust and ranged from 1.4 to 1.8. The significantly smallest average number per stump was found in poplar (1.2). No significant differences were found in terms of the number of stems per stump between the fertilization options. The number of

Table 5. Biometric features of crops after the third year of vegetation.

Species	Soil enrichment procedure	Number of stems (pieces)	Plant height (m)	Stem diameter (mm)
Black locust	C	1.5±0.2	2.4±0.3	20.4±5.3
	L	1.7±0.3	3.2±0.7	25.5±5.1
	F	1.8±0.1	2.4±0.4	21.6±1.8
	L+F	1.8±0.1	3.3±0.1	31.3±4.4
	M	1.5±0.2	2.6±0.5	24.6±5.5
	M+F	1.6±0.1	2.9±0.0	23.6±1.4
	L+M	1.6±0.2	3.1±0.4	28.5±3.2
	L+M+F	1.7±0.2	3.4±0.4	31.3±2.6
Mean		1.6±0.2 **a**	2.9±0.5 **c**	25.9±5.2 **c**
Poplar	C	1.2±0.0	5.2±0.3	43.2±5.3
	L	1.1±0.2	5.4±0.6	43.1±4.6
	F	1.2±0.1	5.3±0.6	45.5±1.5
	L+F	1.2±0.2	6.0±0.2	50.7±7.2
	M	1.2±0.2	5.1±0.5	41.1±2.7
	M+F	1.1±0.1	5.3±0.6	46.3±4.8
	L+M	1.3±0.2	5.4±0.2	41.6±3.3
	L+M+F	1.3±0.2	5.6±0.1	50.4±4.4
Mean		1.2±0.1 **b**	5.4±0.4 **b**	45.2±5.2 **a**
Willow	C	1.4±0.3	5.3±0.2	32.5±2.4
	L	1.4±0.2	6.4±0.2	40.3±7.8
	F	1.6±0.2	5.7±0.7	34.7±4.6
	L+F	1.5±0.1	6.4±0.8	38.2±2.0
	M	1.6±0.4	5.6±0.7	31.9±1.5
	M+F	1.6±0.3	5.7±0.7	38.2±6.4
	L+M	1.7±0.1	6.4±1.2	42.0±13.1
	L+M+F	1.8±0.2	7.0±0.4	41.4±5.3
Mean		1.6±0.2 **a**	6.1±0.8 **a**	37.4±6.6 **b**
Mean	C	1.4±0.2	4.3±1.4 d	32.0±10.6 c
	L	1.4±0.3	5.0±1.5 b	36.3±9.7 b
	F	1.5±0.3	4.5±1.6 d	33.9±10.7 b
	L+F	1.5±0.3	5.2±1.5 a	40.1±9.6 a
	M	1.4±0.3	4.4±1.5 d	32.6±7.8 c
	M+F	1.5±0.3	4.6±1.4 c	36.1±10.8 b
	L+M	1.5±0.2	5.0±1.6 b	37.3±9.6 b
	L+M+F	1.6±0.3	5.4±1.6 a	41.0±9.0 a
Mean		1.5±0.3	4.8±1.5	36.2±9.8

± standard deviation

a. b. c. … homogenous groups

Table 6. Co-relation Coefficient *r* – Pearson for a selection of features.

Specification	Number of plants	Number of stems	Plant height	Stem diameter	Yield of fresh biomass	Yield of dry biomass	Yield energy value	Coal equivalent
Number of plants	1.00	-0.32*	0.81*	0.64*	0.68*	0.68*	0.68*	0.68*
Number of stems	-0.32*	1.00	-0.26*	-0.48*	-0.34*	-0.30*	-0.30*	-0.30*
Plant height	0.81*	-0.26*	1.00	0.77*	0.77*	0.77*	0.77*	0.77*
Stem diameter	0.64*	-0.48*	0.77*	1.00	0.79*	0.77*	0.76*	0.76*
Yield of fresh biomass	0.68*	-0.34*	0.77*	0.79*	1.00	1.00*	1.00*	1.00*
Yield of dry biomass	0.68*	-0.30*	0.77*	0.77*	1.00*	1.00	1.00*	1.00*
Yield energy value	0.68*	-0.30*	0.77*	0.76*	1.00*	1.00*	1.00	1.00*
Coal equivalent	0.68*	-0.30*	0.77*	0.76*	1.00*	1.00*	1.00*	1.00

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

stems per stump was significantly negatively correlated with plant density and height and stem diameter (Table 6).

The stem height and diameter after the third vegetation year varied significantly within species and the fertilization options applied. No significant differences were found for the interactions between them (Table 3). The average plant height after the third vegetation period was 4.8 m and the standard deviation was 1.5 (Table 5). Among the species under study, the willow plants were the highest (6.1 m). The plant height at the control site was 5.3 m and with lignin, mycorrhiza and fertilization it reached 7.0 m. The poplar trees were lower by 0.7 m on average than the willow plants. Among the species under study, the black locust plants were the lowest (2.9 m). An analysis of differences between plant heights at the different fertilization sites showed that the highest plants were obtained at the lignin+mycorrhiza+fertilization site (5.4 m, on average). The same homogeneous group included plants grown at the site with lignin and fertilization used in combination (5.2 m). The lowest plants were obtained at the control site (4.3 m). The plant height was significantly positively correlated with the stem diameter and plant number (Table 6).

The largest stem diameter was found in poplar (45.2 mm) and it was significantly lower (by 7.8 mm) in willow (Table 5). This feature was the lowest in black locust (25.9 mm, on average). Poplar had the thickest stems at the site with lignin, and mineral fertilization used in combination (50.7 mm) and willow had the thickest stems at the site in which lignin and mycorrhiza were used in combination (42.0 mm). The value of this feature in black locust ranged from 20.4 to 31.3 mm, respectively, for the control and at the sites where combinations of lignin with fertilization and lignin with fertilization and mycorrhiza were used. An analysis of the differences between stem thickness at different fertilization sites showed that the thickest stems were obtained at the lignin+mycorrhiza+fertilization site (41.0 mm on average). The thinnest shoots were obtained at the control site (32.0 mm) and at the site with mycorrhiza (32.6 mm).

As in previous years, no significant infestation of the plants under study by diseases or pests was recorded after the third year of vegetation. Therefore, no negative effect of them on the growth or development of plants was observed. It must be stressed that no insecticides or fungicides were used in the experiment for the first three years, and no irregularities in plant growth were observed. Clearly, observations and examinations should be continued in subsequent years of the experiment, but not having to apply pesticides in the production of wooden biomass brought added value, from both environmental and economic perspectives.

Biomass Yield and Its Energy Value

The crop yield and its energy value varied significantly from species to species and from one soil enrichment option to another. No significant differences were found in the interactions between the experiment factors (Table 3). The largest yield after three years of vegetation was obtained in poplar (50.4 $Mg \cdot ha^{-1}$), which was smaller by about 5 $Mg \cdot ha^{-1}$ in willow (Table 7). The yield of fresh wood of black locust was nearly 3.5 times lower than in poplar. Of the methods of soil enrichment applied in the experiment, the largest yield of fresh biomass was obtained at sites with lignin and fertilization. The sites, control and mycorrhiza, were in the final (fourth) homogeneous group. The plant yield was positively correlated with the height, stem diameter and plant number, and it was negatively correlated with the number of stems (Table 6).

When moisture content was taken into account, the dry matter yield lay within a broad range from 6.9 $Mg \cdot ha^{-1}$ in black locust to 23.5 $Mg \cdot ha^{-1}$ in poplar (Table 7). The highest yield in the entire experiment was obtained at the site where poplar was grown and where lignin with fertilization was used in combination (34.5 $Mg \cdot ha^{-1}$ d.m.); the yield of the species at the other sites was lower by 18-51%. The willow yield was lower by 16% to 61%, at the site with lignin and fertilization, and at the control site, respectively, compared to the highest yield of poplar. The yield of dry matter of black locust was lower by up to 61-91%. Converted to the year of the plantation use, the highest average yield of dry biomass was given by poplar at 7.8 $Mg \cdot ha^{-1} \cdot year^{-1}$ (Table 7). The average willow yield was

Table 7. Crop yield after the third 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	6.1±2.4	3.2±1.3	1.1±0.4
	L	14.4±2.5	7.7±1.4	2.6±0.5
	F	6.2±1.3	3.3±0.7	1.1±0.2
	L+F	25.1±4.4	13.3±2.5	4.4±0.8
	M	10.3±5.2	5.5±2.7	1.8±0.9
	M+F	11.5±2.5	6.1±1.3	2.0±0.4
	L+M	10.5±2.1	5.6±1.1	1.9±0.4
	L+M+F	20.1±6.3	10.7±3.4	3.6±1.1
Mean		13.0±7.1 **b**	6.9±3.8 **b**	2.3±1.3 **b**
Poplar	C	37.4±11.3	17.7±5.3	5.9±1.8
	L	58.3±20.4	27.3±9.5	9.1±3.2
	F	60.2±9.6	28.2±4.6	9.4±1.5
	L+F	74.7±29.2	34.5±13.2	11.5±4.4
	M	36.7±6.2	17.4±3.2	5.8±1.1
	M+F	36.4±3.4	17.0±1.5	5.7±0.5
	L+M	42.8±1.8	19.9±0.8	6.6±0.3
	L+M+F	56.8±11.1	26.4±5.1	8.8±1.7
Mean		50.4±18.1 **a**	23.5±8.3 **a**	7.8±2.8 **a**
Willow	C	26.7±10.2	13.4±5.2	4.5±1.7
	L	51.2±6.9	25.3±3.4	8.4±1.2
	F	57.3±28.9	28.6±14.4	9.5±4.8
	L+F	59.1±3.0	29.0±1.5	9.7±0.5
	M	27.9±11.5	13.8±5.8	4.6±1.9
	M+F	40.3±8.6	19.7±4.0	6.6±1.3
	L+M	44.5±11.0	21.8±5.2	7.3±1.7
	L+M+F	57.2±20.2	27.9±9.7	9.3±3.2
Mean		45.5±17.5 **a**	22.4±8.6 **a**	7.5±2.9 **a**
Mean	C	23.4±15.8 d	11.4±7.4 d	3.8±2.5 d
	L	41.3±23.1 b	20.1±10.6 b	6.7±3.6 b
	F	41.3±30.4 b	20.0±14.7 b	6.7±4.9 b
	L+F	53.0±26.5 a	25.6±11.7 a	8.5±3.9 a
	M	25.0±13.6 d	12.2±6.4 d	4.1±2.1 d
	M+F	29.4±14.4 c	14.3±6.6 c	4.8±2.2 c
	L+M	32.6±17.5 c	15.8±8.1 c	5.3±2.7 c
	L+M+F	44.7±22.0 b	21.7±10.1 b	7.2±3.4 b
Mean		36.3±22.4	17.6±10.4	5.9±3.5

± standard deviation
a. b. c. … homogenous groups

Table 8. Biomass energy yield value and its coal equivalent.

Species	Soil enrichment procedure	Yield energy value		Coal equivalent	
		(GJ·ha^{-1})	(GJ·ha^{-1}·year^{-1})	(Mg·ha^{-1})	(Mg·ha^{-1}·year^{-1})
Black locust	C	55.9±21.4	18.6±7.1	2.2±0.9	0.8±0.3
	L	132.9±24.6	44.3±8.2	5.3±1.0	1.8±0.3
	F	56.9±12.3	19.0±4.1	2.3±0.5	0.8±0.2
	L+F	231.4±42.8	77.1±14.3	9.3±1.7	3.1±0.6
	M	94.7±47.2	31.6±15.8	3.8±1.9	1.3±0.6
	M+F	105.5±22.5	35.2±7.5	4.2±0.9	1.4±0.3
	L+M	97.1±19.6	32.4±6.5	3.9±0.8	1.3±0.3
	L+M+F	186.3±59.0	62.1±19.7	7.5±2.4	2.5±0.8
Mean		120.1±65.5 **b**	40.0±21.8 **b**	4.8±2.6 **b**	1.6±0.9 **b**
Poplar	C	298.9±89.4	99.6±29.8	12.0±3.6	4.0±1.2
	L	462.9±161.4	154.3±53.8	18.5±6.5	6.2±2.2
	F	481.6±78.9	160.6±26.3	19.3±3.2	6.4±1.1
	L+F	585.0±219.4	195.0±73.1	23.4±8.8	7.8±2.9
	M	298.1±53.8	99.4±17.9	11.9±2.2	4.0±0.7
	M+F	289.2±24.2	96.4±8.1	11.6±1.0	3.9±0.3
	L+M	336.4±13.0	112.1±4.4	13.5±0.5	4.5±0.2
	L+M+F	448.0±86.9	149.3±29.0	17.9±3.5	6.0±1.2
Mean		400.0±140.1 **a**	133.3±46.7 **a**	16.0±5.6 **a**	5.3±1.9 **a**
Willow	C	230.1±89.9	76.7±30.0	9.2±3.6	3.1±1.2
	L	430.6±56.8	143.5±19.0	17.2±2.3	5.7±0.8
	F	487.1±247.2	162.4±82.4	19.5±9.9	6.5±3.3
	L+F	494.2±24.8	164.7±8.3	19.8±1.0	6.6±0.3
	M	235.7±99.5	78.6±33.2	9.4±4.0	3.1±1.3
	M+F	336.8±66.2	112.3±22.1	13.5±2.7	4.5±0.9
	L+M	376.7±89.9	125.6±30.0	15.1±3.6	5.0±1.2
	L+M+F	478.5±165.2	159.5±55.1	19.1±6.6	6.4±2.2
Mean		383.7±146.1 **a**	127.9±48.7 **a**	15.4±5.8 **a**	5.1±2.0 **a**
Mean	C	195.0±126.1 d	65.0±42.0 d	7.8±5.0 d	2.6±1.7 d
	L	342.1±179.7 b	114.0±59.9 b	13.7±7.2 b	4.6±2.4 b
	F	341.9±250.1 b	114.0±83.4 b	13.7±10.0 b	4.6±3.3 b
	L+F	436.9±194.8 a	145.6±64.9 a	17.5±7.8 a	5.8±2.6 a
	M	209.5±109.1 d	69.8±36.4 d	8.4±4.4 d	2.8±1.5 d
	M+F	243.8±112.1 c	81.3±37.4 c	9.8±4.5 c	3.3±1.5 c
	L+M	270.0±138.9 c	90.0±46.3 c	10.8±5.6 c	3.6±1.9 c
	L+M+F	370.9±170.1 b	123.6±56.7 b	14.8±6.8 b	5.0±2.3 b
Mean		301.3±177.1	100.4±59.0	12.1±7.1	4.0±2.4

± standard deviation
a. b. c. … homogenous groups

slightly lower, 7.5 Mg·ha^{-1}·year^{-1}, whereas the dry matter yield of black locust was merely 2.3 Mg·ha^{-1}·year^{-1}. The highest yield of poplar, willow and black locust was obtained at the sites where lignin was used in combination with fertilization (11.5, 9.7 and 4.4 Mg·ha^{-1}·year^{-1} d.m., respectively). This yield was higher by 95%, 116%, and 300%, respectively, compared to the control site. Of the methods of soil enrichment applied in the experiment, the significantly highest average yield of dry biomass of the species under study was obtained at sites with lignin and fertilization (8.5 Mg·ha^{-1}·year^{-1} d.m.). It was higher by 124% compared to the average yield obtained at the control sites.

The energy value of the biomass yield and its coal equivalent were closely correlated with the yield of each species in different combinations (Table 6). Of the species under study, the highest average energy value of the yield was found for poplar, 400 GJ·ha^{-1}, i.e. 133.3 GJ·ha^{-1}·year^{-1} (Table 8). The energy value of willow biomass was in the same homogeneous group. This value for the black locust was lower by 70% compared to that of poplar. The highest yield energy value in the entire experiment was found for poplar (195 GJ·ha^{-1}·year^{-1}) grown on soil enriched with mineral fertilizers and lignin. The value of the feature at the other sites where poplar was grown was lower by 18-51%. The willow yield energy value was lower than the highest value achieved in the experiment (by 15.5%-61%) and it ranged from 164.7 to 76.7 GJ·ha^{-1}·year^{-1}. The value of this feature for black locust ranged from 18.6 to 77.1 GJ·ha^{-1}·year^{-1}.

In order to illustrate the potential of energy contained in the biomass of the species under study, its coal equivalent was calculated. The analyses demonstrated that the energy value of poplar yield in a three-year harvest rotation was 16 Mg·ha^{-1} of hard coal which, when converted to a year of plantation use was 5.3 Mg·ha^{-1}·year^{-1} (Table 8). An equally high energy yield was obtained from the willow plantation (15.4 Mg·ha^{-1} i.e. 5.1 Mg·ha^{-1}·year^{-1}). These values for black locust were the lowest (4.8 Mg·ha^{-1} i.e. 1.6 Mg·ha^{-1}·year^{-1}). The experiment showed that the optimum combination, at a poor soil site in a three-year harvest rotation for poplar, gave a yield of 23.4 Mg·ha^{-1} Coal eq, i.e. 7.8 Mg·ha^{-1}·year^{-1} Coal eq. The production of biomass of willow, clone UWM 006, under the same conditions, yielded 19.8 Mg·ha^{-1} i.e. 6.6 Mg·ha^{-1}·year^{-1} Coal eq.

Discussion

A farmer will grow a specific perennial energy crop provided it has a high yield and, potentially, a high profit. Therefore, the yield of different plant species is of key importance. According to literature reports, biomass yield depends on a number of factors, such as soil quality, species or cultivar, agrotechnical procedures and their quality, planting density, and biomass harvest cycle. This has been confirmed by a study by Mola-Yudego [20]. The results of the study show average yield increments in Sweden of 2.06 Mg·ha^{-1}·year^{-1} per decade. The yield increase was caused by higher farmer awareness and knowledge of the methods of setting up and running a plantation, as well as by using improved willow cultivars. An increase in biomass productivity was recorded in the group of farmers with experience in growing the crop.

Apart from the productivity in a specific year or the harvest cycle, it is affected by plant survivability, whose consequence is the total yield per hectare during the entire plantation use [21]. Higher plant loss is a consequence of their frequent harvest and a lower survival rate of some cultivars at higher planting densities. However, some cultivars do not tolerate longer rotations and their survival rate in shorter rotations is higher. Moreover, climatic conditions, especially shortages of rainfall, may have a considerable effect on plants taking root [22, 23].

A number of reports have confirmed the great diversity of yield. In their paper, Adegbidi et al. [24] reported that the yield in fertilized and watered plantations in the USA exceeded 27 Mg·ha^{-1}·year^{-1} d.m. On the other hand, a commercial plantation yielded 7.5 Mg·ha^{-1}·year^{-1} d.m. on average in the first crop rotation [2]. Various willow cultivars tested in Wales yielded from 1.17 Mg·ha^{-1}·year^{-1} d.m. in the year when the plantation was set up to 18.5 Mg·ha^{-1}·year^{-1} d.m. in the fourth year of the experiment [25].

Kuś and Matyka [26] determined the productivity of Polish, Swedish, and Danish willow clones. The yield in one-year rotations for all the species was 12.7 Mg·ha^{-1} d.m. on medium soil, 14.1 Mg·ha^{-1} d.m. on light soil, and 14.0 Mg·ha^{-1} d.m. on heavy soil. The average dry matter yield for all the willow clones in a three-year rotation was higher by over 20% than the total yield of three annual harvests.

High variability also has been observed in the yield of poplar grown in short rotations. In a Canadian experiment [1] conducted in a four-year rotation cycle, poplar yielded 66.48-72.20 Mg·ha^{-1} d.m. The yield of 14 clones of poplar grown in China ranged from 0.29 to 22 Mg·ha^{-1}·year^{-1} d.m. [27], whereas in Belgium it ranged from 1.6 to 9.7 Mg·ha^{-1}·year^{-1} [28].

Other studies, as well as these author's findings, have shown a lower yield of black locust grown in short rotations, compared to willow and poplar. According to Aravanopoulos [29], the yield of various cultivars of black locust grown in Greece ranged from 2.90 to 8.98 Mg·ha^{-1}·year^{-1} d.m. The yield of poplar was much higher and ranged from 7.54 to 16.54 Mg·ha^{-1}·year^{-1} d.m. A lower yield of black locust was also achieved in Hungarian studies, it ranging from 6.7 to 9.7 Mg·ha^{-1}·year^{-1} d.m. depending on the cultivar used [10]. On the other hand, lower yield of willow and poplar compared to that of black locust was achieved in Germany when the three species were grown on post-mine soil. This shows the high usability of the species when grown on marginal soils [30].

These authors' experiments have employed different methods of soil enrichment in order to increase the biomass yield, but also to meliorate it. Recent experiments conducted by Quaye and Volk [31] have shown that the use of organic waste materials as nutrient sources for willow biomass production is an attractive means to decrease fertilization costs, increase biomass production, and reduce greenhouse gas emission. A study conducted by Grünewald et al. [30] on the cultivation of SRC in the restoration of post-mining fields has shown that using compost and compost plus mineral fertilization produces higher yields than mineral fertilization alone.

The energy value of the yield obtained in this experiment varied highly depending on the species and the fertilization applied. It ranged from merely 18.6 to 195 GJ·ha^{-1}·year^{-1}, respectively, for black locust grown at the control site and for polar with mineral fertilization and lignin used in combination. An equally high-energy value of poplar yield (188 GJ·ha^{-1}·year^{-1}) was achieved for a crop in a two-year harvest cycle [32]. On the other hand, the energy value of poplar yield in extensive cultivation in a 4-year harvest rotation was much lower (70.9 GJ·ha^{-1}·year^{-1}) [33]. Furthermore, it was shown in another study that the energy balance for a bioenergy system using poplar biomass was better than for the production and distribution of natural gas [34]. The yield energy value for willow production is also strongly diversified by agrotechnical procedures, habitat, weather conditions, and plant harvest cycles. In a study conducted in Poland on an experimental plantation of willow with a three-year harvest rotation depending on these factors, the yield energy value was high and ranged widely (from 188 to 349 GJ·ha^{-1}·year^{-1}) [35, 36]. Only the lower limit of these values was achieved in this study, but it must be emphasized that the plants were grown at a site with poor-quality soil. Meanwhile, the mean net energy from willow plantations in Sweden is approximately 170 GJ·ha^{-1}·year^{-1} [37]. This can be increased to over 200 GJ·ha^{-1}·year^{-1} by using wastewater to irrigate a willow plantation [38]. This hypothesis was confirmed in a study conducted in Canada, in which the energy value of the willow yield obtained in a two-year harvest cycle ranged from 73 GJ·ha^{-1} to 290 GJ·ha^{-1} with the sludge dose of 0 and 300 kg·ha^{-1} N, respectively [39].

Solar energy accumulated in biomass can effectively replace that of fossil fuels, such as hard coal, and it can be effectively used to produce heat, power, and combined heat and power. Such solutions can bring measurable environmental, social, financial, and economic benefits [40]. For example, Krzyżaniak et al. [41] reported that the amount of greenhouse gases emitted in the combustion of willow chips is 18 times smaller per GJ than in the combustion of coal, even if all the GHG emissions during the biomass production and transport are taken into account. The study conducted by Heller et al. [42] has also confirmed that using wood to generate power helps to considerably reduce emissions of unwanted gases to the atmosphere. Owing to co-firing biomass with coal, at a co-firing rate of 10% biomass, the net global warming potential decreases by 7-10%. Moreover, net SO_2 emissions were reduced by 9.5%. In addition, the authors estimated the system performance of using willow biomass in dedicated biomass gasification and direct-fired generating facilities and demonstrated that the pollution avoided is comparable to other renewables such as PV and wind.

The experiment presented here has shown that the optimum combination, at a poor soil site in a three-year harvest rotation for poplar, gave a yield whose energy is equivalent to 23.4 Mg·ha^{-1} i.e. 7.8 Mg·ha^{-1}·year^{-1} of hard coal. Meanwhile, the production of biomass of willow under the same conditions gave a yield with an energy equivalent of 19.8 Mg·ha^{-1} i.e. 6.6 Mg·ha^{-1}·year^{-1} of hard coal. Therefore, such a solution makes it possible to use soil, which is hardly suitable for the cultivation of edible crops, generating potentially considerable profit in the process. Assuming that that the price of medium quality coal is 700 PLN·Mg^{-1}, one can estimate the maximum profit generated by poplar production to amount to approximately 18,720 PLN·ha^{-1}, i.e. 6,240 PLN·ha^{-1}·year^{-1}. The corresponding values for willow would be 15,840 PLN·ha^{-1}, i.e. 5,280 PLN·ha^{-1}·year^{-1}. Moreover, using willow or poplar biomass for energy generation would reduce the greenhouse effect and reduce the emission of sulphur compared to coal combustion.

Conclusions

The use of lignin, mycorrhiza and mineral fertilization had a beneficial effect on the chemical properties of the soils. Compared to the site where the experiment was set up [19] and to the control site, the available macronutriens levels in the soils increased. The fertilization also raised soil pH compared to the control. Applying lignin had a beneficial effect on the organic carbon content and on sorption properties (an increase in the sorption capacity and saturation of the sorption complex with alkaline cations). This shows that the use of lignin in order to improve soil quality is justified.

The yield of the species under study has been shown to vary significantly. This study has also shown that enriching soil with organic carbon (from lignin) helps to increase the productivity of SRWC species (from 54% to 140% compared to control sites). Importantly, the use of lignin provides an added environmental value because it is a kind of industrial waste which can be reused. This study has shown that the species of willow and poplar under study can be grown on poor-quality agricultural land because they provide high yield, high energy, and a high coal equivalent. However, the biomass of black locust may fail to provide sufficient biomass and energy yield to justify setting up a plantation using this species. However, it can be recommended for use on degraded land because it enriches soil with nitrogen and clears soil by means of phytoremediation.

These findings have shown the potential for increasing the yield of SRWC on poor soils, which are hardly usable for growing edible crops. Moreover, they have shown that SRWC studies need to be continued to identify the right species, varieties, clones, and agrotechnical procedures for specific soil conditions, as these factors significantly affect the yield and accumulated plant energy. It must also be stressed that these findings need to be verified in subsequent harvest cycles and during the entire plantation use period, which is the aim of further studies by the authors.

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