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Abstract Biomass is produced as a feedstock for energy generation and industrial processes from short-rotation woody crop plantations in Europe, the USA, and Canada. This study determined the impact of soil enrichment on the survival rate, productivity, energy value, and yield of three species of crops grown on poor soil in a 4-year harvest rotation based on two factors: species (willow, poplar, and black locust) and fertilization (lignin, mineral fertilization, mycorrhiza inoculation, and their combination). The highest average yield was obtained from willow, followed by poplar and black locust. The highest yield in the entire experiment was for poplar with lignin combined with mineral fertilization (10.5 odt ha^{-1} year^{-1}). Using lignin combined with mineral fertilizers increased the yield by 8–14 % compared to mineral fertilizers alone for willow and poplar and nearly doubled the black locust yield. The energy value of the yield ranged from 28.6 to 176.7 GJ ha^{-1} year^{-1}, respectively, for black locust grown on the control plot and for poplar grown with mineral fertilization combined with lignin.

Keywords Willow · Poplar · Black locust · Fertilization · Yield · Yield energy value

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Introduction

Biomass as feedstock for energy generation and industrial processes on short-rotation woody crop (SRWC) plantations is being produced in many countries of Europe [1–5], the USA, and Canada [6–8]. Crops grown in the SRWC system include poplar, willow, and black locust. Poplar is grown mainly in the southern regions of Europe [9–11] and willow in the northern regions. Willow is grown on the largest area in Sweden—about 12,000 ha [1]. This species is also grown in areas exceeding 5,000 ha in Poland and Denmark and between 2,000–4,000 ha in Germany and the UK [12]. However, Hungary has the largest area of black locust plantations, and attempts have been made to grow it as a short-rotation crop for biomass production [13, 14].

SRWC plantations are often established on poor marginal soils (dry, damp, or with poor location) or contaminated soils (unsuitable for the cultivation of edible crops or fodder). Crops used for energy generation or industry should not compete with food production. Nevertheless, plantation owners producing biomass for commercial purposes will seek the highest yield per unit area. Several studies have shown that the yield of SRWC biomass is affected by a number of interrelated factors, including species, cultivar, and cultivation clone [2, 7, 15, 16]. Soil conditions are also a major factor [2, 17]. Other factors which have an impact on the yield of SRWC include planting density and harvest frequency [3, 18], climatic conditions, and agricultural procedures [19–21]. When SRWC are grown on soils of poor quality, the type and dose of fertilizers used are of great importance [1, 22], although some studies have shown the impact of this factor on the yield to be limited [23–25]. In the majority of studies, the effect of mineral fertilization has been compared to fertilization with animal manure or sludge, although there is limited data regarding the effect of soil enrichment by mycorrhizal inoculation or lignin on the productivity of SRWC compared to mineral fertilization. Mycorrhiza may increase the biomass production of SRWC, improve tolerance of abiotic and biotic stress, and increase resistance against soil pathogens [26]. Large volumes of lignin are available in the market; in 2010, the production was approximately 50 million tonnes of extracted lignin, but only 1 million tonne was commercially used for low-value products, the rest was burnt as a low-value fuel [27]. Therefore, low-purity lignin may also find application in improving soil structure and increasing the content of organic carbon to enhance the plant development conditions and their yield. Further, this study sought to determine the effect of soil enrichment on the survival rate, morphological features, yield, and energy value of three species of plants grown on a poor-soil site with low suitability for edible crops.

Materials and Methods

Soil Characteristics

The experiment was located in northeastern Poland (53°59′ N, 21°04′ E) on an experimental field owned by the University of Warmia and Mazury in Olsztyn (UWM). The study area was situated in varied undulating terrain, although the area of the experimental field was relatively flat. The soil analysis showed that the experiment was set up in brunic arenosol (Dystric) soil, formed from sand (Table 1). The soil was periodically too dry, and the level of underground water was below 150 cm. The mesopore content in its surface layers (which is indicative of the amount of water available to plants) in slightly loamy sand was low, and it was very low in the underlying sand. Macropores (19.3–30.4 %) dominated the entire soil profile.

Setting Up and Conducting the Experiment

Winter triticale (× *Triticosecale* Wittm. ex A. Camus) was grown in rotation as forecrop for SRWC. Roundup spray was applied at 5 dm^3 ha^{-1} after the triticale was harvested. Subsequently, after about 3 weeks, discing of the soil was done, and deep ploughing at a depth of 30 cm was done in late autumn 2009. In the second week of April 2010, the field was disced and harrowed, places for planting were marked out, and cuttings of willow and poplar and seedlings of black locust were planted manually. The cuttings were 25 cm in length, and their diameter was 0.9–1.1 cm, whereas rooted seedlings of black locust were about 30–35 cm in height.

Table 1 Soil texture and 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	–	–
	t ha^{-1}	114.1	–	–
N—mineral	mg kg^{-1}	3.90	1.10	0.51
P	mg kg^{-1}	112.2	67.3	22.0
K	mg kg^{-1}	106.2	79.7	21.6
Mg	mg kg^{-1}	66.0	76.0	23.0
B	mg kg^{-1}	6.3	3.3	2.8
Cu	mg kg^{-1}	2.1	1.9	1.2
Zn	mg kg^{-1}	21.5	7.2	4.9
Fe	mg kg^{-1}	1360.0	1380.0	470.0
Soil texture		Slightly loamy sand	Slightly loamy sand	Loose sand
Clay <0.002 mm	%	2	1	0
Silt 0.002–0.05 mm	%	8	9	4
Sand 0.05–2.0 mm	%	90	90	96

Subsequently, after the cuttings of willow and poplar were planted, a solution of soil herbicide Guardian Complete MIX 664 SE with water in 3.5:300 dm^3 ha^{-1} ratio was applied. No herbicide spray was used on the black locust plots. Mechanical weeding was performed three times (last weeks of May, June, and July) during the 2010 growing season.

This study was based on a two-factorial experiment. Three plant species, willow, poplar, and black locust, were the first experiment factor. The willow *Salix viminalis* L., clone UWM 006, was acquired from the UWM. Poplar *Populus nigra* × *Populus maximowiczii* Henry cv. Max-5 was provided by a farm in the north of Austria. Black locust (*Robinia pseudoacacia* L.), a native species, was provided by a forest nursery in Poland.

The other experimental factor was the fertilization method. The following options were identified: lignin (L), mineral fertilization (F), mycorrhiza inoculation (M), lignin + mineral fertilization (LF), mycorrhiza + mineral fertilization (MF), lignin + mycorrhiza (LM), lignin + mycorrhiza + mineral fertilization (LMF), and a control plot with no soil enrichment (C). The experiment was set up in three replications using 18.0-m^2 plots.

Willow cuttings were planted in the conventional twin-row design with a spacing of 0.75 m within twin rows with 1.5 m between pairs of rows. Cuttings were spaced 0.8 m apart within the rows, with 11,000 plants per hectare.

Lignin (a waste product in the process of paper production) was applied in spring (before the experiment) at 13.3 t ha^{-1}. It was scattered on the soil surface with a rear-discharge manure spreader before the discing and harrowing, which effectively mixed it with soil. The lignin applied in the experiment contained 61.72 % organic matter and had acidic pH (4.1 in KCl).

Live mycorrhizal mycelium was applied, separately for each species, in early September 2010, after the willows, poplars, and black locusts had formed sufficient root systems. Inoculation in the form of liquid suspension at 30–35 cm^3 was applied under each plant with a manual applicator (a manual sprayer with a special nozzle for inoculation application into the soil at a depth of 20 cm). In general, one soil injection was made next to each plant so that the inoculation was introduced as close to the root system as possible.

Live mycelium was obtained by reproducing fungi isolated from the roots of *Salix caprea* which grows in Poland, concluding that this helped the willow plants to survive in the harsh conditions of light sandy soil. Genus *Salix* (including species of *Salix viminalis*) is capable of entering into symbiosis with many fungal species, both ectomycorrhizal and endomycorrhizal. For this reason, isolates were used which were the only ones available on the market originating from deeply mycorrhized roots of *S. caprea*. Poplar trees were inoculated with mycelium isolated from the roots of poplar grown as feedstock for energy generation in Spain. Since the plantation was inoculated with an isolate of poplar which grows in Poland, this represented a re-inoculation. The inoculation for black locust was a mixture of mycorrhizal fungi used in forest nurseries. Black locust does not have any species-specific mycorrhiza, and its roots are associated with many fungus species.

No top dressing was applied in the first year of growth because of the slow growth of the plant root systems. However, phosphorus and potassium were spread by hand before the second growing season (2011). Phosphorus was applied at 13 kg ha^{-1} as a triple superphosphate. Potassium was applied at 50 kg ha^{-1} as potassium salt. Nitrogen was applied in two doses. The first dose was applied as ammonium nitrate at 50 kg ha^{-1} immediately before the start of the 2011 growing season. The second nitrogen dose in the same form was applied in mid-June 2011 (40 kg ha^{-1}).

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

After the fourth year of growth (2013), the plant density in each plot (per 1 ha) was determined in early December 2013, and all shoots (only live ones, more than 1.5 m long) were counted per plant. Biometric measurements were performed on ten plants on every plot; the following were measured: plant height and shoot diameter (measurements were made 0.5 m above the ground level). The plant yield was determined by cutting down entire plants with a chain saw 5–10 cm above the ground level. Plants obtained from every plot were weighed with BA 300K electronic scales (manufactured by Axis) within an accuracy of 0.1 kg to determine the fresh biomass yield from a plot. The fresh biomass yield and its moisture content were used to calculate the dry matter biomass yield on each plot. During shoot cutting, biomass samples were taken from each of the plots (approximately 5 kg) for laboratory analyses. The samples were packed in plastic bags and transported to the laboratory. The biomass moisture content was determined in fresh willow chips in a laboratory, with the drying and weighing method according to PN 80/G-04511. Lower heating values of the particular species in the studied combinations were calculated based on the higher heating values (method according to PN-81/G-04513, using IKA C 2000 calorimeter) and moisture content determined in a laboratory. The yield energy value (GJ ha^{-1}) was calculated by multiplying the real lower heating values of fresh biomass of the particular species and treatments (GJ t^{-1}) by its yield (t ha^{-1}).

Statistical Analysis

The experimental data were analyzed statistically using STATISTICA PL software to calculate the mean arithmetic values and standard deviation of the examined traits.

Homogeneous groups for the examined traits were determined by Tukey's (HSD) multiple-comparison test with the significance level set at $P<0.05$. Principal component analysis (PCA) was applied to evaluate experimental traits. A diagram of the component scores for the first two PCs (F1 and F2) is presented in the form of a biplot.

Weather Conditions

The weather conditions for all growing seasons are presented in Fig. 1. The year 2010 was generally mild in terms of the average air temperature. Although the first 2 months may have been colder than average, no spring frost was recorded, and the plants had good thermal conditions for growth and development. The amount of rainfall was higher than the multi-year average, both for the whole year and the growing season. However, its distribution was uneven, which undoubtedly hindered plant growth and development. 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. No additional plant watering was applied in the experiment in order to simulate the potential conditions of a commercial plantation. The subsequent growing seasons—2011, 2012, and 2013—were generally warmer compared to the multi-year period, and the total rainfall was rather beneficial for plant growth.

Results

Survival Rate and the Plant Biometric Features

The number of plants after the fourth growing season varied significantly between species ($P=0.0000$) and between different combinations of the species and methods of soil enrichment ($P=0.0325$) (Table 2). The highest survival rate was found for willow (94.8 %), followed by poplar (92.3 %) and black locust (57.1 %).

The number of shoots on a rootstock ranged from 1.04 to 1.63, with 1.46 and 1.42 found on average in black locust and willow, respectively, and a smaller number on average (1.1) in poplar (Table 3).

The shoot heights and diameters varied significantly between species ($P=0.0000$), soil enrichment ($P=0.0000$ and

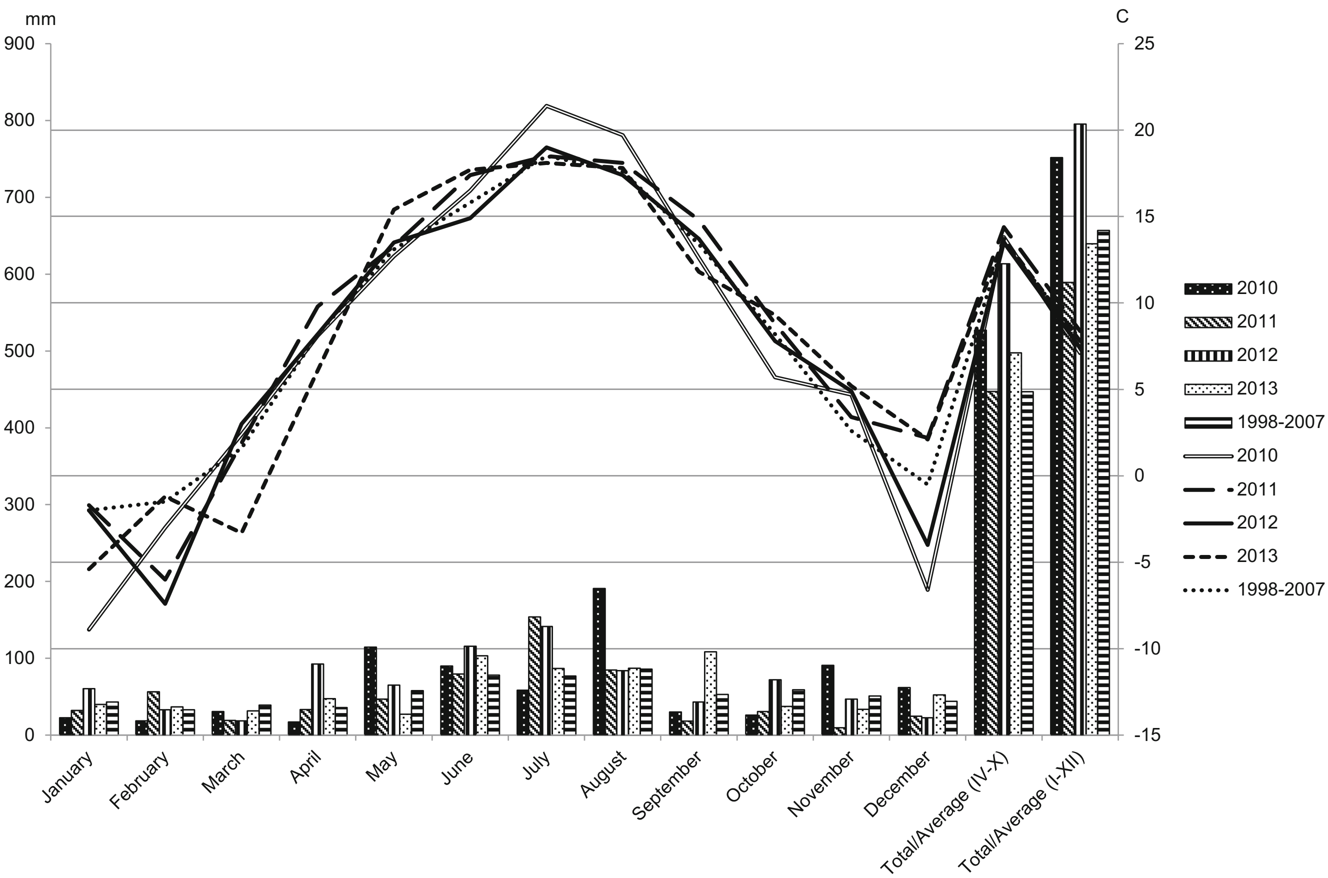

Fig. 1 Weather conditions during the experiment period 2010–2013 and multi-year period 1998–2007. *Bars* represent precipitation; *curves* represent air temperatures

Table 2 Number and survivability of plants after the fourth growing season

Species	Soil enrichment procedure	Number of plants (pieces ha^{-1})	Survivability (%)
Black locust	C	5556±962d	50.0±8.7d
	L	6481±2103d	58.3±18.9d
	F	6296±1156d	56.7±10.4d
	LF	7778±556c	70.0±5.0c
	M	6667±1470cd	60.0±13.2cd
	MF	6111±692d	55.0±8.7d
	LM	5370±642d	48.3±5.8d
	LMF	6481±1398d	58.3±12.6d
Mean		6343±1257B	57.1±11.3B
Poplar	C	10,556±0ab	95.0±0.0ab
	L	10,185±1156ab	91.7±10.4ab
	F	10,185±321ab	91.7±2.9ab
	LF	10,556±556ab	95.0±5.0ab
	M	10,741±321ab	96.7±2.9ab
	MF	10,185±1156ab	91.7±10.4ab
	LM	9630±849b	86.7±7.6b
	LMF	10,000±556ab	90.0±5.0ab
Mean		10,255±695A	92.3±6.3A
Willow	C	9815±1786ab	88.3±16.1ab
	L	10,185±849ab	91.7±7.6ab
	F	10,926±321a	98.3±2.9a
	LF	10,000±962ab	90.0±8.7ab
	M	10,556±556ab	95.0±5.0ab
	MF	11,111±0a	100.0±0.0a
	LM	10,926±321a	98.3±2.9a
	LMF	10,741±321ab	96.7±2.9ab
Mean		10,532±827A	94.8±7.4A
Mean for soil enrichment procedure	C	8642±2548	77.8±22.9
	L	8951±2247	80.6±20.2
	F	9136±2241	82.2±20.2
	LF	9444±1416	85.0±12.7
	M	9321±2148	83.9±19.3
	MF	9136±2423	82.2±21.8
	LM	8642±2578	77.8±23.2
	LMF	9074±2115	81.7±19.0
		P-value	
Species (A)		0.0000	0.0000
Soil enrichment procedure (B)		0.5766	0.5766
AB		0.0325	0.0325

Mean±standard deviation. Values followed by uppercase letters indicate homogenous groups factor A and factor B. Values followed by lowercase letters indicate homogenous groups interaction AB. Significant at $P<0.05$

$P=0.0006$, respectively), and the interactions between them ($P=0.0397$ and $P=0.0308$, respectively) (Table 3). The willows were the tallest (6.94 m on average). The average plant height was the lowest on the control plot (6.09 m) and the highest on the LMF plot (7.94 m). The poplar trees were lower by 0.1 m on average than the willow plants, and they were included in the same homogeneous group. The poplar height ranged from 6.47 to 7.14 m in different combinations of soil enrichment. It should be emphasized that the height of the poplar trees was less varied than that of the willows, which is shown by the standard deviation values. The black locusts were the shortest (3.30 m on average).

The largest shoot diameter was found in poplar (52.62 mm on average), while willows were smaller (by 10.36 mm on

Table 3 Biometric features of crops after the fourth growing season

Species	Soil enrichment procedure	Number of shoots (pieces)	Shoot height (m)	Shoot diameter (mm)
Black locust	C	1.48±0.04ab	2.85±0.57d	26.24±8.23d
	L	1.43±0.21ab	3.46±0.57d	31.65±9.25cd
	F	1.37±0.32b	2.78±0.30d	26.93±5.34d
	LF	1.47±0.15ab	3.76±0.32d	37.63±1.77bc
	M	1.51±0.12a	3.28±0.37d	31.55±3.04cd
	MF	1.28±0.07b	3.05±0.13d	32.78±3.17cd
	LM	1.55±0.31a	3.56±0.66d	36.08±5.54c
	LMF	1.57±0.15a	3.64±0.27d	34.49±4.04c
Mean		1.46±0.19A	3.30±0.51B	32.17±6.06C
Poplar	C	1.04±0.07c	6.47±0.22bc	47.25±4.69b
	L	1.10±0.10c	7.14±0.43b	50.16±9.37b
	F	1.14±0.15bc	6.86±0.41b	54.23±1.87ab
	LF	1.13±0.12bc	7.13±0.12b	57.90±3.48a
	M	1.07±0.06c	6.58±0.50bc	48.01±4.99b
	MF	1.10±0.10c	6.70±0.33b	57.03±5.25a
	LM	1.10±0.00c	6.79±0.38b	50.10±3.64b
	LMF	1.10±0.10c	7.04±0.26b	56.29±2.25a
Mean		1.10±0.09B	6.84±0.38A	52.62±5.79A
Willow	C	1.37±0.12b	6.09±0.20c	36.59±3.50c
	L	1.37±0.12b	7.55±0.42ab	49.30±8.20b
	F	1.44±0.22ab	6.17±0.37bc	38.41±4.75c
	LF	1.34±0.07b	7.29±0.55ab	42.55±4.85bc
	M	1.33±0.32b	6.31±0.66bc	35.63±2.05c
	MF	1.37±0.06b	6.57±0.67b	40.07±5.85c
	LM	1.50±0.00a	7.57±0.64ab	46.57±12.95b
	LMF	1.63±0.12a	7.94±0.78a	48.97±9.08b
Mean		1.42±0.17A	6.94±0.84A	42.26±7.95B
Mean for soil enrichment procedure	C	1.29±0.21	5.13±1.75B	36.69±10.40B
	L	1.30±0.20	6.05±2.00A	43.70±11.92AB
	F	1.32±0.25	5.27±1.92B	39.86±12.44AB
	LF	1.31±0.18	6.06±1.76A	46.03±9.67A
	M	1.30±0.26	5.39±1.65AB	38.40±8.04AB
	MF	1.25±0.13	5.44±1.83AB	43.29±11.58AB
	LM	1.38±0.26	5.97±1.91A	44.25±9.63AB
	LMF	1.43±0.27	6.21±2.01A	46.58±10.87A
P-value				
Species (A)		0.0000	0.0000	0.0000
Soil enrichment procedure (B)		0.3143	0.0000	0.0006
AB		0.0415	0.0397	0.0308

Mean±standard deviation. Values followed by uppercase letters indicate homogenous groups factor A and factor B. Values followed by lowercase letters indicate homogenous groups interaction AB. Significant at $P<0.05$

average), but the smallest diameters were found in black locust (32.17 mm on average) (Table 3). Poplar trees developed the thickest shoots on the LF plot (57.90 mm) and willow on the L plot (49.30 mm), while black locust shoot diameters ranged from 26.24 to 37.63 mm on the C and LF plots, respectively.

Biomass Yield and Energy Value

The oven dry biomass yield differed significantly between the species (P=0.0000), soil enrichment (P=0.0000), and between their interactions (P=0.0002) (Table 4). The highest average yield was obtained from willow (8.34 odt

Table 4 Crop yield after the fourth growing season

Species	Soil enrichment procedure	Yield (odt ha^{-1})	Yield (odt ha^{-1} year^{-1})
Black Locust	C	6.54±1.98f	1.63±0.49f
	L	10.89±2.59ef	2.72±0.65ef
	F	8.16±3.10f	2.04±0.77f
	LF	21.59±1.51d	5.40±0.38d
	M	10.78±1.70ef	2.70±0.43ef
	MF	9.43±3.64ef	2.36±0.91ef
	LM	9.88±1.21ef	2.47±0.30ef
	LMF	14.59±0.83e	3.65±0.21e
Mean		11.48±4.87B	2.87±1.22B
Poplar	C	21.91±2.24d	5.48±0.56d
	L	36.64±1.90b	9.16±0.48b
	F	36.82±1.55b	9.21±0.39b
	LF	41.96±1.84a	10.49±0.46a
	M	25.51±3.00cd	6.38±0.75cd
	MF	34.03±0.99b	8.51±0.25b
	LM	28.60±2.85c	7.15±0.71c
	LMF	37.40±2.29ab	9.35±0.57ab
Mean		32.86±6.78A	8.21±1.69A
Willow	C	20.39±1.16d	5.10±0.29d
	L	37.28±4.01ab	9.32±1.00ab
	F	36.32±4.68b	9.08±1.17b
	LF	39.32±1.91a	9.83±0.48a
	M	22.41±6.28d	5.60±1.57d
	MF	34.18±1.09b	8.55±0.27b
	LM	35.80±7.94b	8.95±1.98b
	LMF	41.20±3.97a	10.30±0.99a
Mean		33.36±8.27A	8.34±2.07A
Mean for soil enrichment procedure	C	16.28±7.51D	4.07±1.88D
	L	28.27±13.29B	7.07±3.32B
	F	27.10±14.50B	6.78±3.63B
	LF	34.29±9.71A	8.57±2.43A
	M	19.57±7.62C	4.89±1.91C
	MF	25.88±12.49BC	6.47±3.12BC
	LM	24.76±12.35BC	6.19±3.09BC
	LMF	31.06±12.68AB	7.77±3.17AB
		P-value	
Species (A)		0.0000	0.0000
Soil enrichment procedure (B)		0.0000	0.0000
AB		0.0002	0.0002

Mean±standard deviation. Values followed by uppercase letters indicate homogenous groups factor A and factor B. Values followed by lowercase letters indicate homogenous groups interaction AB. Significant at $P<0.05$

ha^{-1} year^{-1}); poplar yield was similar (8.21 odt ha^{-1} year^{-1}), whereas the yield of black locust was 2.87 odt ha^{-1} year^{-1}. The highest yield of poplar was obtained on the LF plot (10.49 odt ha^{-1} year^{-1}), although it was 39.2 and 47.8 % lower on the M and C plots, respectively. The highest yield of willow was obtained on the LMF plot (10.3 odt ha^{-1} year^{-1}). This was included in the same homogeneous group as the highest yield of poplar and willow from the LF plot. The lowest yield of willow was obtained on the C and M plots (by 50.5 and 45.6 %), respectively, than the highest yield of the species. The highest yield of black locust was obtained on the LF plot (5.4 odt ha^{-1} year^{-1}).

The lower heating value of biomass was significantly differentiated by the species (P=0.0000), while soil enrichment and interactions between factors were insignificant (P=0.2129 and P=0.6321, respectively) (Table 5). However, the energy value of the biomass yield was significantly differentiated by the species (P=0.0000), soil enrichment (P=0.0000), and between their interactions (P=0.0002). The highest yield energy value was found for poplar (176.7 GJ ha^{-1} year^{-1}) grown on the LF plot. It was 11–48 % lower on other poplar plots. The willow yield energy value was 1–51 % lower than the highest value achieved in the experiment, and it ranged from 175.1 to 87.4 GJ ha^{-1} year^{-1}. The energy value

Table 5 Lower heating value and biomass energy yield value

Species	Soil enrichment procedure	Lower heating value (GJ t^{-1})	Yield energy value (GJ ha^{-1})	(GJ ha^{-1} year^{-1})
Black locust	C	10.10±0.15	114.4±34.7f	28.6±8.7f
	L	10.12±0.01	190.0±45.2ef	47.5±11.3ef
	F	10.27±0.14	144.1 ± 54.4f	36.0±13.6f
	LF	10.19±0.14	379.3±25.7d	94.8±6.4d
	M	10.16±0.01	189.6±29.7ef	47.4±7.4ef
	MF	10.12±0.08	165.9±64.3f	41.5±16.1f
	LM	10.21±0.15	173.4±21.3ef	43.3±5.3ef
	LMF	10.12±0.08	256.1±15.4e	64.0±3.8e
Mean		10.16±0.11A	201.6±85.6B	50.4±21.4B
Poplar	C	7.48±0.05	370.1±37.6d	92.5±9.4d
	L	7.46±0.15	617.9±30.8b	154.5±7.7b
	F	7.45±0.09	620.4±26.2b	155.1±6.5b
	LF	7.45±0.07	706.7±32.1a	176.7±8.0a
	M	7.46±0.07	429.5±49.2cd	107.4±12.3cd
	MF	7.38±0.07	571.2±17.8b	142.8±4.5b
	LM	7.42±0.03	481.0±47.9c	120.3±12.0c
	LMF	7.43±0.04	629.1±38.8ab	157.3±9.7ab
Mean		7.44±0.07C	553.2±113.9A	138.3±28.5A
Willow	C	8.51±0.04	349.8±19.1d	87.4±4.8d
	L	8.44±0.07	635.5±68.5ab	158.9±17.1ab
	F	8.51±0.04	620.5±81.1b	155.1±20.3b
	LF	8.40±0.06	669.8±31.5a	167.4±7.9a
	M	8.46±0.12	381.7±106.1d	95.4±26.5d
	MF	8.41±0.05	581.4±18.9b	145.3±4.7b
	LM	8.35±0.05	607.6±133.6b	151.9±33.4b
	LMF	8.37±0.02	700.5±68.2a	175.1±17.0a
Mean		8.43±0.08B	568.3±140.1A	142.1±35.0A
Mean for soil enrichment procedure	C	8.70±1.15	278.1±126.1C	69.5±31.5C
	L	8.67±1.17	481.2±222.8B	120.3±55.7B
	F	8.74±1.23	461.7±243.5B	115.4±60.9B
	LF	8.68±1.21	585.3±157.5A	146.3±39.4A
	M	8.69±1.18	333.6±125.4C	83.4±31.4C
	MF	8.64±1.2	439.5±208.1BC	109.9±52.0BC
	LM	8.66±1.23	420.7±206.3BC	105.2±51.6BC
	LMF	8.64±1.18	528.5±210.5AB	132.1±52.6AB
P-value				
Species (A)		0.0000	0.0000	0.0000
Soil enrichment procedure (B)		0.2129	0.0000	0.0000
AB		0.6321	0.0002	0.0002

Mean±standard deviation. Values followed by uppercase letters indicate homogenous groups factor A and factor B. Values followed by lowercase letters indicate homogenous groups interaction AB. Significant at P<0.05

for black locust was the lowest, and it ranged from 94.8 to 28.6 GJ ha^{-1} year^{-1}.

Principal component analysis revealed that the variability of the plant species under study can be 80.5 % explained by the first principal component (F1) through strong correlation of the yield structure features (number of plants, height, diameter), biomass yield, lower heating value, and the yield energy value. The number of shoots was the second component (F2); it contributed another 13.5 % to the explanation of the variability of the plots under study (Table 6).

The biplot graph clearly shows the separation of the species under study (three separate "point isles") (Fig. 2). In the top left-hand corner, there are points assigned to poplar on various enrichment plots, which indicates that the species was characterized by a small number of shoots and by the lowest lower heating value, high yield-forming parameters, and a high yield energy value. The points assigned to willow are in the bottom left-hand corner, which means that the species had a high yielding and energy potential, and it differed from poplar by having a large number of shoots. Black locust forms the third separate group of points. As well as having the highest lower heating value, the yield and yield energy values were the lowest and were considerably below the potential of willow and poplar.

Discussion

Since growing a specific SRWC crop offers a high yield and potentially high profits, the yields of different plant species are of key importance. Apart from productivity in a specific year or harvest cycle, the yield is affected by the presence of pathogens and the plant vigor associated with it. No significant infestation of the plants under study by diseases or pests was recorded during the four growing seasons. However, observations must be conducted because the literature data mentioned considerable damage caused by pests and diseases on SRWC plantations [2, 28–30]. It should be noted that SRWC plantations are sometimes eaten by wild animals (deer, wisent, and elk) [31]. In our experiment, losses in black locust caused by wild animals and low precipitation in the setup year of the experiment resulted in a decrease in the total yielding potential.

Table 6 Row factorial loadings

Traits	F1	F2
Number of plants (NoP)	*−0.93*	−0.09
Plant height (PH)	*−0.97*	−0.12
Stem diameter (D)	*−0.91*	0.22
Number of shoots (NoS)	0.54	*−0.83*
Yield of dry biomass (YB)	*−0.96*	−0.23
Yield energy value (YE)	*−0.96*	−0.24
Lower heating value (LHV)	*0.95*	−0.25
Eigenvalue λ_i	5.64	0.95
Share (%)	80.54	13.52

Italics indicate significant coefficients. Significant at $P<0.05$

The methods of soil enrichment used in the experiment resulted in yield diversification (from 1.6 to 10.5 odt ha^{-1} year^{-1}) among different species and soil enrichment procedures. Such a wide yield diversity for different species indicates that there is a need for further studies to confirm and verify the data in subsequent harvest rotations. On the other hand, it must be emphasized that other publications have confirmed the significant diversification of yield depending on the SRWC species and the amount of fertilizers applied. On a willow plantation in sandy soil in Denmark, the average annual biomass production ranged from 8.7 odt ha^{-1} year^{-1} in the control up to 11.9 odt ha^{-1} year^{-1} fertilized with 60 kg N ha^{-1} year^{-1} [22]. Similarly, a high willow yield was achieved in the USA from 8.4 on control plots to between 9 and 11.6 odt ha^{-1} year^{-1} with different applications of NPK [32]. In a study conducted in central Sweden [1], the yield for two varieties of willow obtained on the plots under control conditions was similar to the willow yield obtained on the control plot in this study. The willow yield increased significantly depending on the intensity of fertilization and its strategy. In the economic treatment, the average yield was 9.3 odt ha^{-1} year^{-1}, whereas it was 10.8 odt ha^{-1} year^{-1} in the normal treatment and 13.2 odt ha^{-1} year^{-1} for the intensive treatment [1]. Also, high yield for four willow clones (average 14.1 odt ha^{-1} year^{-1}) grown on very good soil and fertilized was obtained in a 4-year harvest cycle [33].

A high yield of poplar biomass was obtained in a 4-year harvest cycle in Canada for the clone NM *P. maximowiczii* × *P. nigra* (NM6) (18.0 odt ha^{-1} year^{-1}) [8]. A similar yield was found for poplar grown in the same cutting cycle in Italy [34]. A very high yield of six genotypes of poplar in three consecutive 2-year harvest rotations was obtained by Sabatti et al. [35]. Biomass production differed significantly among the rotations, starting from 16 odt ha^{-1} year^{-1} in the first year, peaking at 20 odt ha^{-1} year^{-1} in the second, and decreasing to 17 odt ha^{-1} year^{-1} in the third rotation. However, other authors have reported that seven poplar clones of *Populus* × *canadensis* and seven of the *Populus deltoides* grown in Italy did not give such a high yield [36]. The yield of poplar obtained in other studies also varied depending on the climatic conditions, the type of soil, species, and clone, harvest rotation, age of the plantation, level of fertilization, and other agricultural procedures [37–39].

Black locust is an important species in land reclamation and potentially as a species to produce biomass on poor-quality soils. In Hungary, black locust obtained in a 5-year harvest rotation at a density of about 22,000 plants per hectare gave a yield of 6.5 odt ha^{-1} year^{-1} [14]. However, when grown at two lower densities, the yields were 33–51 % lower.

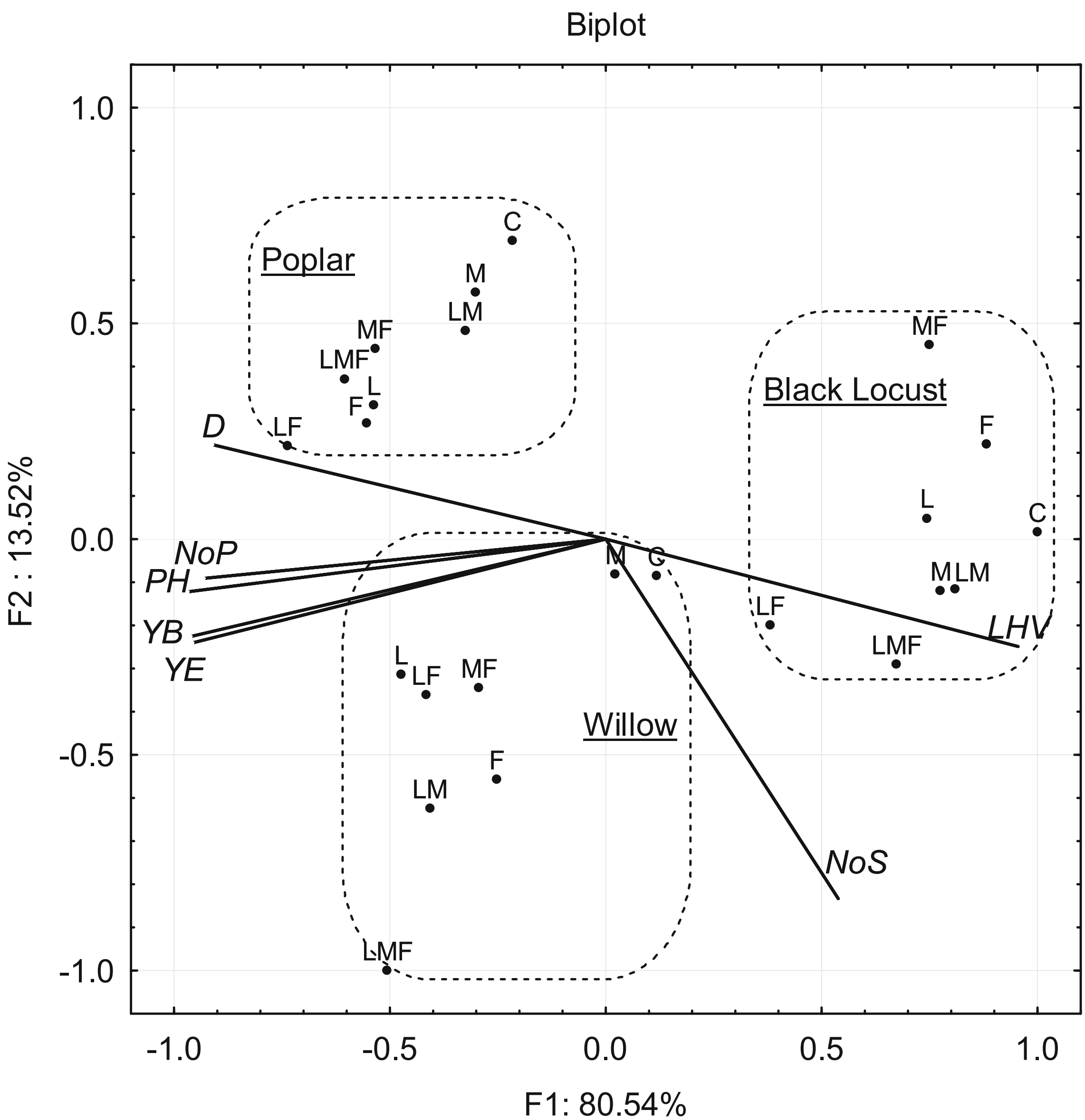

Fig. 2 Biplot for analyzed data. *D* diameter, *NoP* number of plants, *PH* height, *YB* biomass yield, *YE* energy yield, *NoS* number of shoots, *LHV* lower heating value

Gruenewald et al. [40] conducted a study with black locust planted on poor-quality soil at a former brown coal opencast mine. The average yield in a 3-year rotation was approximately 4 and 6 odt ha^{-1} year^{-1} in a 6-year rotation. Black locust gave a higher yield than poplar and willow despite the low quality of soil and disadvantageous climatic conditions. Moreover, these results show that black locust adapts well to sandy sites which are poor in nutrients, which was confirmed in later studies [41].

The energy value of the yield in this experiment ranged from 28.6 to 176.7 GJ ha^{-1} year^{-1}. A high energy value for the poplar yield of 188 GJ ha^{-1} year^{-1} was achieved in the production of the crop in a 2-year harvest cycle [42]. On the other hand, the energy value of the poplar yield obtained in extensive cultivation in a 4-year harvest rotation was much lower (70.9 GJ ha^{-1} year^{-1}) [43]. This was confirmed by Dillen et al. [39] who showed that the energy value of the yield of poplar grown on degraded land was about 91.8 GJ ha^{-1} year^{-1}. The values were comparable with the energy value of the poplar yield obtained on the control plot in this experiment. In a study conducted in Poland on an experimental willow plantation, the yield energy value was high and lay within a wide range (from 188 to 349 GJ ha^{-1} year^{-1}) [33, 44]. Furthermore, the energy value of the yield of willow grown on a commercial plantation in a 3-year cycle ranged from 46.3 to 242.5 GJ ha^{-1} year^{-1} [4]. The mean net energy from willow plantations in Sweden was approximately 170 GJ ha^{-1} year^{-1} [45]. This may even exceed 200 GJ ha^{-1} year^{-1} when waste water is used for willow plantation irrigation [46]. A positive effect of using sludge was confirmed in a study conducted in Canada, in which the energy value of the willow yield ranged from 73 to 290 GJ ha^{-1} $year^{-1}$ with a sludge dose of 0 and 300 kg N ha^{-1}, respectively [47].

Conclusions

This study found considerable diversity in the productivity and energy value of the SRWC yield not only between species but also depending on the soil enrichment methods and the interactions between these factors. Principal component analysis clearly showed the distinction between the three species under study. It was shown that soil enrichment by using lignin, mycorrhiza, and mineral fertilization can significantly increase the productivity of SRWC species compared to control plots. It must be emphasized that various combinations of mineral fertilization, mycorrhiza, and lignin contributed to a threefold increase in the yield of black locust compared to the control plot and more than a twofold increase for poplar and willow. Importantly, the use of lignin in combination with mineral fertilizers resulted in an increase in the yield by 8–14 % compared to mineral fertilizers alone for willow and poplar and in a nearly twofold increase for black locust. In conclusion, these findings indicate the possibility of increasing productivity and energy value of the SRWC yield on poor soils, with low usability for edible crops, by choosing the right species of woody crops and the method of soil enrichment.

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