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Analysis of the energy efficiency of short rotation woody crops biomass as affected by different methods of soil enrichment

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ABSTRACT

The aim of this study was to determine the energy input and energy efficiency of the production of willow, poplar and black locust chips in four-year harvest rotation. The highest energy input was made in poplar production when soil was enriched with lignin and by mineral fertilisation (33.02 GJ ha^{-1}). For willow production it was 30.76 GJ ha^{-1} when lignin, mycorrhiza and mineral fertilisation were used. The energy input in the production of black locust was much lower. The largest energy gain was obtained in the production of poplar when soil was enriched with lignin and mineral fertilisation (673.7 GJ ha^{-1}). A similar level of this parameter (669.7 GJ ha^{-1}) was achieved in the production of willow when lignin, mycorrhiza and mineral fertilisation was used. In general, a higher energy gain was obtained in the production of willow and poplar than in the production of black locust. On the other hand, the best energy efficiency ratio was achieved for willow (28.9) in the option with lignin. The ratio for poplar production ranged from 19.7 to 25.9. On the other hand, the energy efficiency ratio for black locust ranged from 10.6 to 21.7.

1. Introduction

Government institutions all over the world have become greatly interested in recent years in reducing greenhouse gas emissions and biomass use is seen as a key method of reducing CO_2 emission [1]. According to Directive 2009/28/EC, the contribution of renewable energy to the overall energy balance in the EU should reach 20% and 10% in the transport sector for total fuel consumption [2]. On the other hand, 136 billion of litres of fuel in the USA is to be obtained from renewable sources in 2022 [3]. It is estimated that 17–30 million ha of land will be needed in Europe and 16–21 million ha in the USA to achieve the goals [4,5]. It must be stressed that food production should always be a priority, so cultivation of Short Rotation Woody Crops (SRWC) should be carried out on marginal soils, which are usually referred to as having low agro-economic value for major agricultural crops [6]. Ghezehei et al. [6] quotes numerous studies which estimate the global resources of marginal land where energy crops could be produced from 100 million up to 1 billion ha.

As has been already mentioned, marginal land is of low utility value and, in consequence, the yield of crops grown on such land is reduced [7]. An increase in yield can be achieved by using mineral fertilisers, lignin or mycorrhiza in the cultivation of SRWC, which has been confirmed in previous studies [8]. Moreover, it is a key issue in setting up an SRWC plantation to select cultivars which give high and stable yield [9]. Nonhebel [10] notes that there is no physiological difference in growing plants for food production and as energy crops. The same plants can even be used for both purposes, for example, rapeseed, which recent publications have mentioned as being an object of interest in regard to energy efficiency [11,12].

The energy efficiency ratio of biomass is mainly influenced by the crop species and production regime. The production technology determines the demand for energy (energy input) and the amount of energy accumulated in biomass (energy output) [12–14]. SRWC must have a much higher energy output level than energy input level to be a real alternative to fossil fuels and to annual energy crops. Therefore, SRWC should have high productivity and calorific value, which would result in high energy efficiency of biomass production and in some environmental benefits. To achieve this, it

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is necessary to carry out multi-factorial studies which include different variables that could influence biomass yield. To date, studies have mainly analysed the effect of a cultivar and harvest cycle on energy efficiency of biomass, without the effect of fertilisation being taken into account [9,15–17]. Our study focuses on assessment of new methods of soil enrichment by the application of lignin, mycorrhiza inoculation and mineral fertilisation, which can affect the energy efficiency of SRWC biomass production. Therefore, the main aim of this study was to determine the energy input and energy efficiency of the production of willow, poplar and black locust chips, depending on the method of soil enrichment applied in a four-year harvest cycle.

2. Materials and methods

2.1. Field experiment

The study was based on a strict field experiment carried out in the years 2010–2013, at a research station located in the north-east of Poland (53°59′ N, 21°04′ E) owned by the University of Warmia and Mazury in Olsztyn (UWM). The experiment was carried out on a poor soil site (Brunic Arenosol (Dystric)) formed from loose sand. Detailed data on the soil properties, weather conditions and the experimental procedure are presented in Table 1 and in the paper [18].

The first experimental factor were three SRWC species: willow (*Salix viminalis*, clone UWM 006), poplar (*Populus nigra* x *P. Maximowiczii Henry* cv. Max-5) and black locust (*Robinia pseudoacacia*). All species were planted at a density of 11.11 thousand ha^{-1}. Planting was done in strips, with two rows in a strip spaced every 0.75 m, then 1.50 m of space separating the next 2 rows in a strip with 0.75 m space between them, etc. Plants in a row were spaced every 0.8 m.

The method of soil enrichment, referred to as "fertilisation", was the second factor. This factor included the following options: application of lignin (L), mineral fertilisation (F), inoculation with mycorrhiza (M), lignin + mineral fertilisation (LF), mycorrhiza + mineral fertilisation (MF), lignin + mycorrhiza (LM); lignin + mycorrhiza + mineral fertilisation (LMF) and control, with no soil enrichment (C). Descriptions of the experiment results, as well as tables and illustrations regarding the methods of soil enrichment, mainly use the abbreviations provided in brackets in the above sentence.

Lignin as paper production residue was applied at 13.3 Mg ha^{-1} in spring 2010 before the experiment was set up. Live mycorrhiza was applied separately for each species in early September 2010. An inoculation in the form of liquid suspension at 30–35 cm^3 was applied under each plant with a manual applicator. Mineral fertilisation was applied before the beginning of the second year of vegetation (2011). Phosphorus (P_2O_5) was applied at 30 kg ha^{-1} as triple superphosphate and potassium (K_2O) at 60 kg ha^{-1} was applied 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 plant vegetation started in 2011. The remaining amount of nitrogen was applied in the same form (40 kg ha^{-1}) in mid-June 2011.

2.2. Energy output analysis

The yield energy value SRWC was calculated as the product of fresh biomass yield (fresh matter - f.m.) per ha and its lower heating value (1):

$$Y_{ev} = Y_b \cdot Q_i^r \tag{1}$$

where:

Y_{ev} – biomass yield energy value (GJ ha^{-1}),
Y_b – fresh biomass yield (Mg ha^{-1} f.m.),
$Q^r{}_i$ – biomass lower heating value (GJ Mg^{-1}).

2.3. Energy input analysis

The energy inputs used to produce the willow, poplar and black locust chips were analysed, including several energy sources: direct energy carriers (diesel fuel), exploitation of fixed assets (tractors, machines, equipment), consumption of materials (mineral fertilisers, agrochemicals, cuttings) and human labour (2).

$$E_{i\ total} = E_{i\ diesel} + E_{i\ fixed\ assets} + E_{i\ materials} + E_{i\ human\ labour} \tag{2}$$

where:

$E_{i\ total}$ – total energy input for SRWC chips production (GJ ha^{-1}),
$E_{i\ diesel}$ – energy input for diesel fuel consumption (GJ ha^{-1}),
$E_{i\ fixed\ assets}$ – energy input for fixed assets (GJ ha^{-1}),
$E_{i\ materials}$ – energy input for materials (GJ ha^{-1})
$E_{i\ human\ labour}$ – energy input for human labour (GJ ha^{-1})

The total energy input for SRWC chips production was calculated based on the unit consumption of materials and the energy intensity of their production. The energy conversion coefficients for diesel fuel (43.1 MJ kg^{-1}), nitrogen fertilizers (48.99 MJ kg^{-1} N), phosphorus fertilizers (15.23 MJ kg^{-1} P_2O_5), potassium fertilizers (9.68 MJ kg^{-1} K_2O) and pesticides (268.4 MJ kg^{-1} of active substance) were based on the indexes presented by Neeft et al. [19]. The energy input for the use of tractors (125 MJ kg^{-1}), machines (110 MJ kg^{-1}) and human labour (60 MJ h^{-1}) in the production process has been calculated with the coefficients provided in the literature and data provided in materials published by manufacturers of tractors and machines [20,21]. The energy input for 1 kg of

Table 1
Weather conditions and some soil properties during the experiment period.

Year	Weather conditions				Soil properties for horizon A (0–21 cm)
	Temperature (°C)		Precipitation (mm)		
	Average (IV-X)	Average (I-XII)	Sum (IV-X)	Sum (I-XII)	
2010	13.8	7.1	527.2	751.8	pH (KCl): 7.05
2011	14.4	8.4	447.3	589.1	Organic matter (%): 2.85
2012	13.5	7.4	613.6	795.3	Soil texture (%):
2013	13.7	7.8	497.5	639.4	clay: 2
Multi-period 1998–2007	13.5	7.9	447.0	657.0	silt: 8
					sand: 90

Table 2
Data for field operations.

Operation	Tractor/Harvester				Machinery		Operating period	Comments	Source data
	Name	Mass (kg)	Power (kW) (max/used)	Utilisation of the power capacity (%)	Name	Mass (kg)	(h ha^{-1})		
Spraying	New Holland TM 130 HP	5465	95.6/47.8	50	Krukowiak sprayer, working width 18 m	2110	0.2	Glyphosate, Roundup 360 SL, 5 l ha^{-1}	This study
Winter ploughing	New Holland TM 175 HP	7150	128.6/90.0	70	Kverneland PG 100 plough, working width 2 m	1120	1.5	5-ridge plough, ploughing depth 30 cm	This study
Fertilisation	New Holland TM 130 HP	5465	95.6/47.8	50	Rauch 3,0 t spreader, working width 18 m	350	2.0	Application of lignin, 13.3 Mg ha^{-1}	This study
Disking (2×)	New Holland TM 130 HP	5465	95.6/60.2	63	Kverneland disk harrow, working width 4 m	1160	1.4	2 × coverage	This study
Harrowing (2×)	New Holland TM 130 HP	5465	95.6/52.6	55	Harrow, working width 6 m	530	1.0	2 × coverage	This study
Marking planting spots	New Holland TM 130 HP	5465	95.6/57.4	60	3-tooth subsoiled U435/1 KRET	730	2.0		This study
Manual planting	Planting time 1 person 22.2 h ha^{-1} for willow and poplar and 74.1 h ha^{-1} for black locust							Planting density 11,111 cuttings per ha	This study
Spraying[a]	New Holland TM 130 HP	5465	95.6/47.8	50	Krukowiak sprayer, working width 18 m	2110	0.2	Soil-applied herbicide, Guardian CompleteMix 664 SE, 3.5 l ha^{-1}	This study
Weeding (3×)	New Holland TM 90 HP	4410	66.0/33.0	50	Mechanical weeder P 430/2, working width 3 m	340	3.0	3 × coverage	This study
Manual application of mycorrhiza	–	–	–	–	Manual applicator	2,5	24.7	Application of inoculation as liquid suspension at 333.3 l ha^{-1}	This study
Fertilisation	New Holland TM 130 HP	5465	95.6/47.8	50	Rauch 3,0 t spreader, working width 18 m	350	1.3	Mineral fertilisation in spring 2011, N – 90; P_2O_5 – 30; K_2O – 60 kg ha^{-}	Own research [9]
Liquidation of plantation	New Holland TM 175 HP	7150	128.6/90.0	70	Rototiller FV 4088, working width 40 cm	1160	6.0	Breaking up larger rootstocks along rows	Own research [9]
Harvesting	Claas Jaguar 830	10,150	236.0/212.4	90	–	–	0.6–4.7	Depending on the yield of a SRWC species, average productivity of harvester 20 ton of chips per hour	Own research [9]]
Field transport	New Holland TM 130 HP	5465	95.6/47.8	50	T 169/2 tractor trailer, loading capacity: 4 tons of chips	1940	0.6–4.7	To ensure continuity of receipt of chips 3 transportation units	Own research [9]

[a] No spraying was done on black locust.

cuttings was as 3.04 MJ [9]. The types of equipment used in field operations and the maximum power of the tractors and harvester and those used in different operations are shown in Table 2.

2.4. Energy efficiency analysis

Accumulated energy gain was the difference between the SRWC yield energy value and the total input for its production (3):

$$E_g = Y_{ev} - E_{i\ total} \quad (3)$$

where:

E_g – accumulated energy gain (GJ ha^{-1}),
Y_{ev} – biomass yield energy value (GJ ha^{-1}),
$E_{i\ total}$ – total energy input (GJ ha^{-1}).

Energy intensity was the energy consumption per 1 Mg of fresh matter (f.m.) or dry matter (d.m.) SRWC chips, it was the ratio of total energy input to the yield (4):

$$EI = E_{i\ total}/Y_b \quad (4)$$

where:

EI – energy intensity (GJ Mg^{-1} f.m. or d.m.),
$E_{i\ total}$ – total energy input (GJ ha^{-1}),
Y_b – biomass yield (Mg ha^{-1} f.m. or d.m.).

Diesel fuel consumption per 1 Mg of fresh or dry SRWC chips, was the ratio of the diesel fuel consumption to the yield (5):

$$C'_D = C_D/Y_b \quad (5)$$

where:

C_D' – diesel fuel consumption (kg Mg^{-1} f.m. or d.m.),
C_D – diesel fuel consumption (kg ha^{-1}),
Y_b – biomass yield (Mg ha^{-1} f.m. or d.m).

The energy efficiency ratio of SRWC chips production was the ratio of the yield energy value (energy output) to energy input for its production (6):

$$ER = Y_{ev}/E_{i\ total} \quad (6)$$

where:

ER – energy efficiency ratio of SRWC chips production,
Y_{ev} – biomass yield energy value (GJ ha^{-1}),
$E_{i\ total}$ – total energy input (GJ ha^{-1}).

2.5. Statistical analysis

The results of fresh biomass yield, lower heating value and yield energy value were analysed 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 $P < 0.05$.

3. Results and discussion

3.1. Biomass yield of SRWC and energy output

The yield of SRWC was significantly differentiated by the species ($P = 0.0000$) and the method of soil enrichment ($P = 0.0000$) and within the interactions between these experiment factors ($P = 0.0003$) (Table 3). As many as 13 homogeneous groups were identified in the fresh mass yield. The significantly largest yield of fresh mass was obtained for poplar grown in the LF option, 94.87 Mg ha^{-1}. A second homogeneous group (ab), with a yield laying in the range of 79.76–84.65 Mg ha^{-1} included poplar grown in the L, F and LMF options and willow grown in the LF and LMF option. The poplar yield was the significantly lowest in the C option

Table 3
Yield of fresh biomass, lower heating value and yield energy value of black locust, poplar and willow in a four-year harvest rotation depending on the soil enrichment procedure.

Species	Soil enrichment procedure	Yield of fresh biomass (Mg ha^{-1})	Lower heating value (GJ Mg^{-1}) [18]	Yield energy value (GJ ha^{-1}) [18]
Black Locust	C	11.30 ± 3.35^{g}	10.1 ± 0.15^{a}	114.4 ± 34.7^{f}
	L	18.78 ± 4.46^{fg}	10.1 ± 0.01^{a}	190.0 ± 45.2^{ef}
	F	14.04 ± 5.32^{g}	10.3 ± 0.14^{a}	144.1 ± 54.4^{f}
	LF	37.24 ± 3.00^{ef}	10.2 ± 0.14^{a}	379.3 ± 25.7^{d}
	M	18.67 ± 2.95^{fg}	10.2 ± 0.01^{a}	189.6 ± 29.7^{ef}
	MF	16.37 ± 6.25^{g}	10.1 ± 0.08^{a}	165.9 ± 64.3^{f}
	LM	16.98 ± 1.98^{g}	10.2 ± 0.15^{a}	173.4 ± 21.3^{ef}
	LMF	25.30 ± 1.33^{f}	10.1 ± 0.08^{a}	256.1 ± 15.4^{e}
Poplar	C	49.46 ± 5.09^{de}	7.5 ± 0.05^{c}	370.1 ± 37.6^{d}
	L	82.87 ± 4.77^{ab}	7.5 ± 0.15^{c}	617.9 ± 30.8^{b}
	F	83.24 ± 3.06^{ab}	7.5 ± 0.09^{c}	620.4 ± 26.2^{b}
	LF	94.87 ± 3.79^{a}	7.4 ± 0.07^{c}	706.7 ± 32.1^{a}
	M	57.65 ± 7.15^{d}	7.5 ± 0.07^{c}	429.5 ± 49.2^{cd}
	MF	77.41 ± 2.16^{b}	7.4 ± 0.07^{c}	571.2 ± 17.8^{b}
	LM	64.85 ± 6.42^{cd}	7.4 ± 0.03^{c}	481.0 ± 47.9^{c}
	LMF	84.65 ± 5.31^{ab}	7.4 ± 0.04^{c}	629.1 ± 38.8^{ab}
Willow	C	41.11 ± 2.37^{e}	8.5 ± 0.04^{b}	349.8 ± 19.1^{d}
	L	75.31 ± 7.76^{b}	8.4 ± 0.07^{b}	635.5 ± 68.5^{ab}
	F	72.89 ± 9.22^{bc}	8.5 ± 0.04^{b}	620.5 ± 81.1^{b}
	LF	79.76 ± 4.32^{ab}	8.4 ± 0.06^{b}	669.8 ± 31.5^{a}
	M	45.18 ± 12.92^{e}	8.5 ± 0.12^{b}	381.7 ± 106.1^{d}
	MF	69.13 ± 2.37^{c}	8.4 ± 0.05^{b}	581.4 ± 18.9^{b}
	LM	72.78 ± 16.02^{bc}	8.3 ± 0.05^{b}	607.6 ± 133.6^{b}
	LMF	83.69 ± 8.08^{ab}	8.4 ± 0.02^{b}	700.5 ± 68.2^{a}

Mean ± standard deviation; [a,b,c]. Homogenous groups.

(49.46 Mg ha^{-1}), and that of willow was the lowest in the C and M options (41.11 Mg ha^{-1} and 45.18 Mg ha^{-1}, respectively). The lowest yield of fresh mass was obtained from black locust. The yield for the species was in the last four homogeneous groups and ranged from 11.30 Mg ha^{-1} to 37.24 Mg ha^{-1}, in the C and LF option, respectively. In a different experiment, in the cultivation of willow in a 4-year harvest rotation at a very good soil site, a very high yield of fresh biomass was obtained, which ranged from 93 to 123 Mg ha^{-1}, depending on the willow clone [22]. An equally high yield (about 120 Mg ha^{-1} f.m.) was obtained from black locust grown in 6-year harvest rotation [17]. An even higher yield (about 180 Mg ha^{-1}) was obtained for poplar grown in the same harvest rotation [16]. However, Wilkinson et al. [23] analysed the effect of density and cultivar on the parameters of biomass of willow grown in northern England in a 3-year harvest rotation and obtained much lower yield, ranging from 34.22 Mg ha^{-1} to 58.60 Mg ha^{-1}.

The lower heating value of biomass was significantly differentiated only by species ($P = 0.0000$), while soil enrichment and interactions between factors were insignificant. The highest lower heating value, ranging from 10.1 to 10.3 GJ Mg^{-1}, was recorded for the biomass of black locust. A second homogeneous group in regard to this feature included biomass of willow (8.3–8.5 GJ Mg^{-1}). On the other hand, the lower heating value for poplar biomass was the significantly lowest and ranged from 7.4 to 7.5 GJ Mg^{-1} (Table 3).

The energy value of the biomass yield was significantly differentiated by the species ($P = 0.0000$) and the method of soil enrichment ($P = 0.0000$) and within interactions between these experiment factors ($P = 0.0002$) (Table 3). The highest energy value in the four-year harvest cycle was recorded for poplar grown in the LF option (706.7 GJ ha^{-1}). The energy value of the yield in the other combinations in which poplar was grown was lower by 11–48%. The first homogeneous group (a) included the energy value of the yield of willow grown in the LF and LMF options (669.8 GJ ha^{-1} and 700.5 GJ ha^{-1}, respectively). The energy value of the yield in the other combinations was lower than the highest value by 1–51%. On the other hand, the energy value of the yield of black locust was the lowest and it ranged from 114.4 to 379.3 GJ ha^{-1}, in the C and LF objects, respectively.

Literature reports have also confirmed that the energy value of SRWC biomass is strongly differentiated by the species, cultivar, harvest cycle and other agrotechnical factors. The energy value of the yield of willow harvested in a 3-year rotation was significantly differentiated by cultivars and it ranged from 138.8 GJ ha^{-1} in cultivar UWM 155–727.4 GJ ha^{-1} in cultivar UWM 006 [9]. On the other hand, the energy value of the yield of *Salix viminalis* obtained in a two-year harvest cycle ranged from 146 GJ ha^{-1} to 580 GJ ha^{-1} [24]. Furthermore, in the cultivation of willow in a 4-year harvest rotation at a very good soil site, a very high energy value of biomass was obtained (nearly 970 GJ ha^{-1} on average), with values ranging from 843 to 1130 GJ ha^{-1}, depending on the willow clone [22]. Nassi o Di Nasso et al. [25] analysed the effect of harvest rotation cycles (annual, biannual, triennial) on the energy balance of a 12-year-old short-rotation coppice poplar with mineral fertilisation, and obtained the highest biomass energy value (1348.7 GJ ha^{-1}) after the first triennial cutting cycle. However, in the second, third and last triennial cutting cycles, the energy value of the yield decreased to 1051.4, 866.7 and 379.8 GJ ha^{-1}, respectively, which resulted in an average of 303.9 GJ ha^{-1} year^{-1} during the whole period of the plantation use. In other studies with poplar coppice grown in Italy in different harvest cycles, with mineral fertilisation and watering, the energy value of the biomass was similar (257 GJ ha^{-1} year^{-1} [15] and 270 GJ ha^{-1} year^{-1}) [16]. Therefore, it was much more than obtained in this experiment in the best option (LF) for poplar (176.7 GJ ha^{-1} year^{-1}). The energy yield in the cultivation of black locust in a 6-year harvest rotation was 190 GJ ha^{-1} year^{-1} [17], which is twice as much as achieved in our experiment in the best soil enrichment option (LF). Such great diversity in the amount of energy obtained per unit area was largely caused by the selection of species and cultivars, agrotechnical measures, harvest cycle, the quality of soil and considerable differences between weather conditions in Poland and Italy, which have a great effect of biomass yield and the energy accumulated in it.

3.2. Energy inputs

The energy inputs for setting up, running and liquidation of 1 ha of SRWC plantation were differentiated by the species and methods of soil enrichment. They were the lowest for willow grown at the

Table 4
Energy input for setting up and running willow, poplar and black locust plantations in the first year of vegetation and for their liquidation (MJ ha^{-1}).

Operation	Willow[a]					Poplar[a]	Black locust[a]
	Labour	Tractors + Machinery	Diesel fuel	Materials	Total	Total	Total
Spraying (glyphosate)	18.0	57.8	87.8	483.1	646.7	646.7	646.7
Winter ploughing	102.0	265.7	1262.9	–	1630.6	1630.6	1630.6
Disking (2×)	96.0	191.3	774.1	–	1061.4	1061.4	1061.4
Harrowing (2×)	72.0	91.2	482.7	–	645.9	645.9	645.9
Marking planting spots	126.0	274.5	1053.2	–	1453.6	1453.6	1453.6
Manual planting	1333.3	–	–	633.3	1966.6	2177.8	5459.3
Spraying[b]	18.0	57.8	87.8	617.3	780.9	780.9	–
Weeding (3×)	198.0	250.0	908.8	–	1356.9	1356.9	1356.9
Liquidation of plantation	372.0	1978.1	5051.6	–	7401.7	7401.7	7401.7
Total of control (C)	2335.3	3166.4	9708.8	1733.8	16,944.3	17,155.4	19,656.1
Per year of plantation use 1/20 Σ	116.8	158.3	485.4	86.7	847.2	857.8	982.8
Application of lignin	180.0	159.1	877.6	0.0	1216.8	1216.8	1216.8
Total lignin (L)	2515.3	3325.6	10,586.4	1733.8	18,161.1	18,372.2	20,872.9
1/20 Σ	125.8	166.3	529.3	86.7	908.1	918.6	1043.6
Application of mycorrhiza	1482.0	6.8	0.0	1066.7	2555.4	2555.4	2555.4
Total mycorrhiza (M)	3817.3	3173.2	9708.8	2800.4	19,499.8	19,710.9	22,211.6
1/20 Σ	190.9	158.7	485.4	140.0	975.0	985.5	1110.6
Total LM	3997.3	3332.4	10,586.4	2800.4	20,716.6	20,927.7	23,428.3
1/20 Σ	199.9	166.6	529.3	140.0	1035.8	1046.4	1171.4

[a] Data for willow broken down into energy flows and their sum, whereas only total energy inputs for individual operations are given for poplar and black locust.
[b] No spraying was done on black locust.

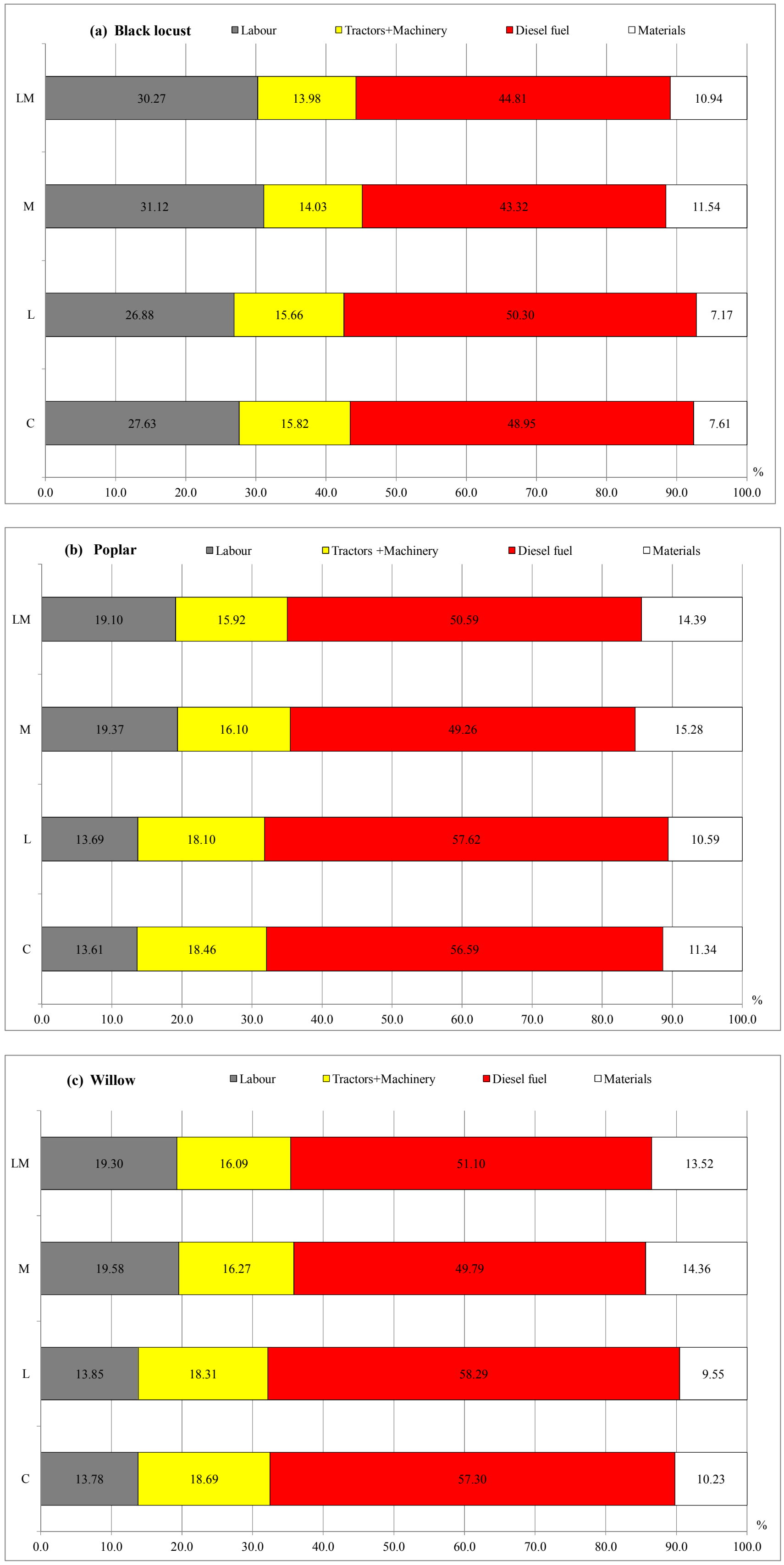

Fig. 1. Structure of energy input (%) for setting up and running a black locust (a), poplar (b) and willow (c) plantation in the first year of vegetation and for their liquidation in the energy flow.

Table 5
Energy input for the production of black locust, poplar and willow chips in a four-year harvest rotation depending on the soil enrichment method by energy flow (MJ ha^{-1}).

Species	Soil enrichment procedure	Energy stream					Total
		Human labour	Tractors + machinery	Diesel	Materials from 1st year	Fertilisers	
Black locust	C	1221.6	1256.2	3908.7	299.3	0.0	6685.7
	L	1347.3	1708.2	5398.5	299.3	0.0	8753.4
	F	1344.4	1513.6	4960.6	299.3	5446.8	13,564.7
	LF	1658.9	2848.7	9212.5	299.3	5446.8	19,466.1
	M	1606.4	1671.5	5203.5	512.6	0.0	8994.0
	MF	1668.8	1646.0	5370.6	512.6	5446.8	14,644.8
	LM	1622.2	1608.7	5083.0	512.6	0.0	8826.5
	LMF	1812.0	2179.1	7114.1	512.6	5446.8	17,064.7
Poplar	C	1060.6	3411.4	10,631.2	389.0	0.0	15,492.2
	L	1497.5	5319.6	16,675.6	389.0	0.0	23,881.7
	F	1556.0	5412.0	17,135.6	389.0	5446.8	29,939.4
	LF	1731.5	6097.0	19,354.2	389.0	5446.8	33,018.5
	M	1455.2	3872.5	12,069.2	602.3	0.0	17,999.2
	MF	1782.4	5085.7	16,110.8	602.3	5446.8	29,028.0
	LM	1577.7	4308.9	13,510.2	602.3	0.0	19,999.1
	LMF	1905.2	5524.2	17,558.4	602.3	5446.8	31,037.0
Willow	C	960.4	2942.3	9164.0	346.8	0.0	13,413.5
	L	1406.8	4895.2	15,348.3	346.8	0.0	21,997.1
	F	1431.7	4830.6	15,317.1	346.8	5446.8	27,372.9
	LF	1550.2	5248.3	16,699.5	346.8	5446.8	29,291.6
	M	1305.6	3172.1	9878.4	560.1	0.0	14,916.2
	MF	1683.0	4620.8	14,656.6	560.1	5446.8	26,967.4
	LM	1672.8	4754.1	14,902.6	560.1	0.0	21,889.6
	LMF	1893.7	5470.2	17,389.2	560.1	5446.8	30,760.0

control site, 16,944 MJ ha^{-1} (Table 4). They increased in the object in which lignin, mycorrhiza and lignin and mycorrhiza in combination were applied before the plantation was set up (by 7%, 15% and 22%, respectively). The energy inputs for setting up and running a poplar plantation during the first year of vegetation and its liquidation after its exploitation was completed at the control site were 17,155 MJ ha^{-1} and 19,656 MJ ha^{-1} for the black locust plantation. As with willow, soil enrichment in poplar and willow cultivation resulted in an increase in energy inputs. The energy inputs calculated per year of plantation use (when a plantation was exploited for 20 years) ranged from 847 to 1171 MJ ha^{-1}, for willow at the control site and for black locust at the site where lignin and mycorrhiza were applied in combination.

Fig. 1 presents the structure of energy input for setting up and running a SRWC plantation in the first year of vegetation and for their liquidation in the energy flow. Diesel fuel consumption dominated all energy inputs and accounted for 43.3%–58.3% of the total inputs, for black locust at site M and willow at site L, respectively. Energy inputs associated with using tractors and machines accounted for 14%–18.7%, for black locust at site LM and willow at site C, respectively. The inputs associated with human labour were much higher for black locust (26.9–31.1%) than for willow and poplar (13.6–19.6%) because of the longer time of planting of black locust seedlings. On the other hand, consumption of materials throughout the whole experiment accounted for 7.2–15.3%. In another experiment, the energy inputs for setting up and running 1 ha of a plantation of willow during the first year of vegetation and its liquidation after its exploitation was completed were similar and amounted to 20,368 MJ ha^{-1} [9]. In terms of energy flows, the consumption of diesel fuel dominated in the structure of energy inputs – 45.9%, followed by materials – 32.6%.

Energy inputs for the production of SRWC chips in a four-year harvest cycle were significantly differentiated by species, methods of soil enrichment and the resulting yield level. The lowest energy inputs were made at control sites. The total energy inputs for the production of black locust chips ranged between 6685.7 MJ ha^{-1} and 19,466.1 MJ ha^{-1} for the C and LF options, respectively (Table 5). The quantities for poplar were 15,492.2 MJ ha^{-1} and 33,018.5 MJ ha^{-1}, respectively. The total energy inputs for willow in the C option amounted to 13,413.5 MJ ha^{-1}, and they were the highest in the LMF option, in which lignin, mycorrhiza and mineral fertilisation were applied in combination (30,760.0 MJ ha^{-1}).

In another experiment, the total energy input in willow chip production was differentiated by cultivar and ranged from 13,675 MJ ha^{-1} to 30,378 MJ ha^{-1}, for the UWM 155 and UWM 006 cultivars, respectively [9]. Furthermore, the energy input in extensive cultivation of willow without fertilisation, weed control or irrigation, was similar to that made in our experiment at the control site and amounted to 14,144 MJ ha^{-1} [26]. On the other hand, total energy input for biomass production in poplar cultivation in a two- and six-year harvest cycle with mineral fertilisation and watering amounted to 29,600 and 91,200 MJ ha^{-1} [15]. Furthermore, the total energy input for setting up and running a plantation of black locust in a six-year cycle was much lower (55,800 MJ ha^{-1}) because a black locust plantation does not require top dressing, irrigation or disease control [17].

Structure of energy input for the production of black locust, poplar and willow chips depending on the soil enrichment procedure by energy flow are presented in Fig. 2. Energy flows in the production of willow and poplar chips, and in most options of the production of black locust chips, were dominated by the consumption of diesel fuel. Consumption of diesel fuel accounted for 54.3% to nearly 69.8% of energy flows in the production of willow and poplar chips, for willow grown in the MF option and for willow and poplar grown in variants with lignin, respectively. On the other hand, the consumption of diesel fuel accounted for 36.7% to nearly 61.7% of energy flows in the production of black locust chips, for the MF and L options, respectively. Energy input for mineral fertilisation in options which involved its application accounted for 16–20% of the total input in production of willow and poplar and 28–40% in the production of black locust. On the other hand, energy input associated with use of tractors and machines ranged between 11 and 19% for black locust and 17–22% for willow and poplar. Furthermore, human labour accounted for 5–9% of the total input in willow and poplar production and 9–18% in black locust production.

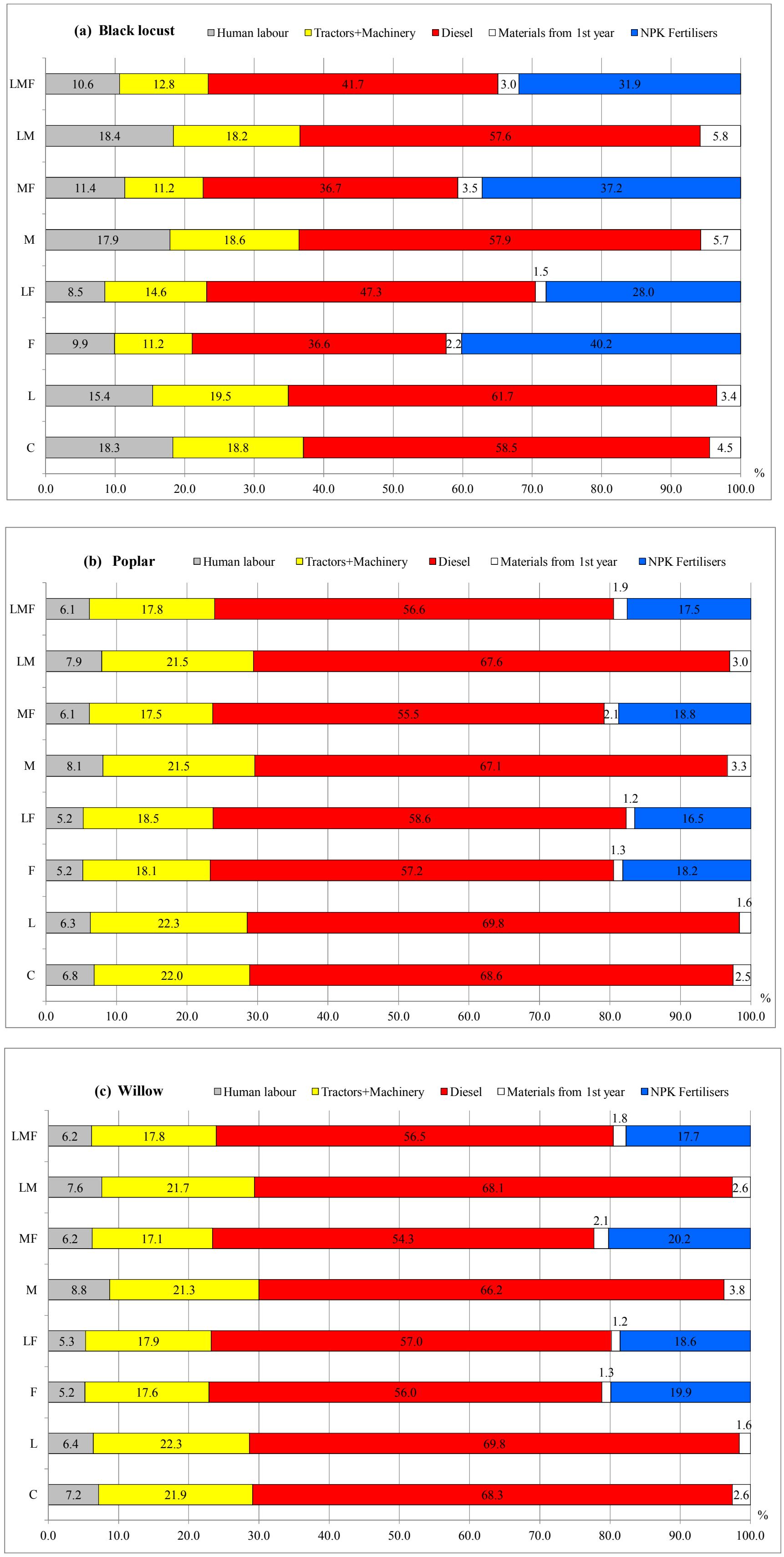

Fig. 2. Structure of energy input (%) for production of black locust (a), poplar (b) and willow (c) chips in a four-year harvest rotation depending on the soil enrichment procedure by energy flow.

Table 6
Energy input for the production of black locust, poplar and willow chips in a four-year harvest rotation depending on the soil enrichment procedure by production operations (MJ ha^{-1}).

Species	Soil enrichment procedure	Production operation				Total
		Setting up and liquidation	Fertilisation	Harvesting	Field transport	
Black locust	C	3931.2	0.0	1752.6	1001.9	6685.7
	L	4174.6	0.0	2913.3	1665.5	8753.4
	F	3931.2	6210.7	2177.8	1245.0	13,564.7
	LF	4174.6	6210.7	5777.7	3303.1	19,466.1
	M	4442.3	0.0	2896.0	1655.7	8994.0
	MF	4442.3	6210.7	2539.8	1452.0	14,644.8
	LM	4685.7	0.0	2634.6	1506.2	8826.5
	LMF	4685.7	6210.7	3924.6	2243.7	17,064.7
Poplar	C	3431.1	0.0	7673.9	4387.2	15,492.2
	L	3674.4	0.0	12,856.9	7350.3	23,881.7
	F	3431.1	6210.7	12,914.4	7383.2	29,939.4
	LF	3674.4	6210.7	14,718.7	8414.7	33,018.5
	M	3942.2	0.0	8943.8	5113.2	17,999.2
	MF	3942.2	6210.7	12,009.4	6865.8	29,028.0
	LM	4185.5	0.0	10,061.4	5752.2	19,999.1
	LMF	4185.5	6210.7	13,132.7	7508.0	31,037.0
Willow	C	3388.9	0.0	6378.2	3646.4	13,413.5
	L	3632.2	0.0	11,684.7	6680.2	21,997.1
	F	3388.9	6210.7	11,308.3	6465.0	27,372.9
	LF	3632.2	6210.7	12,374.2	7074.4	29,291.6
	M	3900.0	0.0	7009.1	4007.1	14,916.2
	MF	3900.0	6210.7	10,725.1	6131.6	26,967.4
	LM	4143.3	0.0	11,291.1	6455.2	21,889.6
	LMF	4143.3	6210.7	12,983.3	7422.6	30,760.0

Energy input in SRWC chips production by operation in mineral fertilisation was the same for all species (6210.7 MJ ha^{-1}). However, the energy input associated with plant harvest and field transport of chips varied (Table 6). The differences were recorded between the species and methods of soil enrichment due to their diverse yield and the consequent time of work of the harvester and the ancillary equipment. The structure of the energy flow by production operations in willow and poplar was dominated by the total input attributable to harvesting and field transport (Fig. 3). It ranged between 62.5% and 83.5% for the MF and L options, respectively, and was 65.0% and 84.6% for poplar, respectively. However, mineral fertilisation accounted for the majority of energy input (range 31.9–45.8%) in those options in the production of lower-yielding black locust in which mineral fertilisation was applied (Fig. 3). Furthermore, when no mineral fertilisation was applied, the highest energy input for the production of black locust chips was recorded for setting up and liquidation of the plantation (range 47.7–58.8%). The energy input for harvesting black locust and field transport of locust ranged from 25.2% to 52.3% for options F and L, respectively. Therefore, energy input associated with mineral fertilisation and setting up the plantation dominated in the production of lower-yielding black locust. However, the proportion of this input decreased in the production of willow and poplar (higher yield) and the input associated with the use of cutters, tractors and transport trailers increased.

Similar relationships were observed in the production of the highest-yielding cultivars of willow in a three-year rotation where the total input attributable to harvesting and field transport dominated (over 60%). On the other hand, mineral fertilisation accounted for the largest part of the energy input in the production of the lowest-yielding cultivars (over 40%) [9]. The energy flows in the production of the lower-yielding cultivars were also dominated by the cost of fertilisers (42–45%). This proportion decreased in the highest-yielding cultivars, to be replaced by growing inputs of energy resulting from the consumption of diesel fuel and the use of machines. Moreover, Heller et al. [27] reported that the structure of energy carriers in the production of willow biomass was dominated by fuels (46%), followed by fertilisation (37%). It has been shown in research into poplar that the largest part of energy input (44%) was linked to cultural operations and 24.5% to harvesting and transport [16]. On the other hand, mineral fertilisation (32.8%) and harvest and transport (26.7% combined) were shown to dominate in energy inputs in the production of black locust [17].

The experiment conducted for this study and the literature data have shown that energy input in the production of SRWC chips can vary and can be affected by multiple factors. The more important factors include the chips production technology, use of machines, different powered tractors and the efficiency of fuel consumption. Therefore, it must be emphasised that the use of more modern equipment of better efficiency can help to achieve lower energy input, with consequent better energy efficiency. Another important element is the layout of the plantation from which the biomass is to be obtained. If a plantation is small or if its shape is irregular, there are a lot of “idle runs”, in which no plants are harvested and which increase the unit energy intensity. Weather conditions during the harvest are also very important. Plants are harvested in winter and the lowest energy intensity is achieved with frozen soil and no snow cover. However, if soil is not frozen or if a soil cover is thick, the time of machine operation is long and fuel consumption grows, which increases the energy intensity of chips production. The plant species, harvest cycle and related morphological features of plants (such as the height and diameter of shoots and skills of the machine operator) also affect the energy intensity of chips production. Therefore, energy consumption, as measured in this experiment could have been different if different equipment had been used in the production of SRWC chips and if the harvest had been carried out in different weather conditions.

3.3. Energy efficiency

The energy input and the yield with its energy value differentiated the energy efficiency of the species under study and the methods of soil enrichment (Table 7). The highest energy gain was obtained in the production of poplar in the LF option, 673.7 GJ ha^{-1},

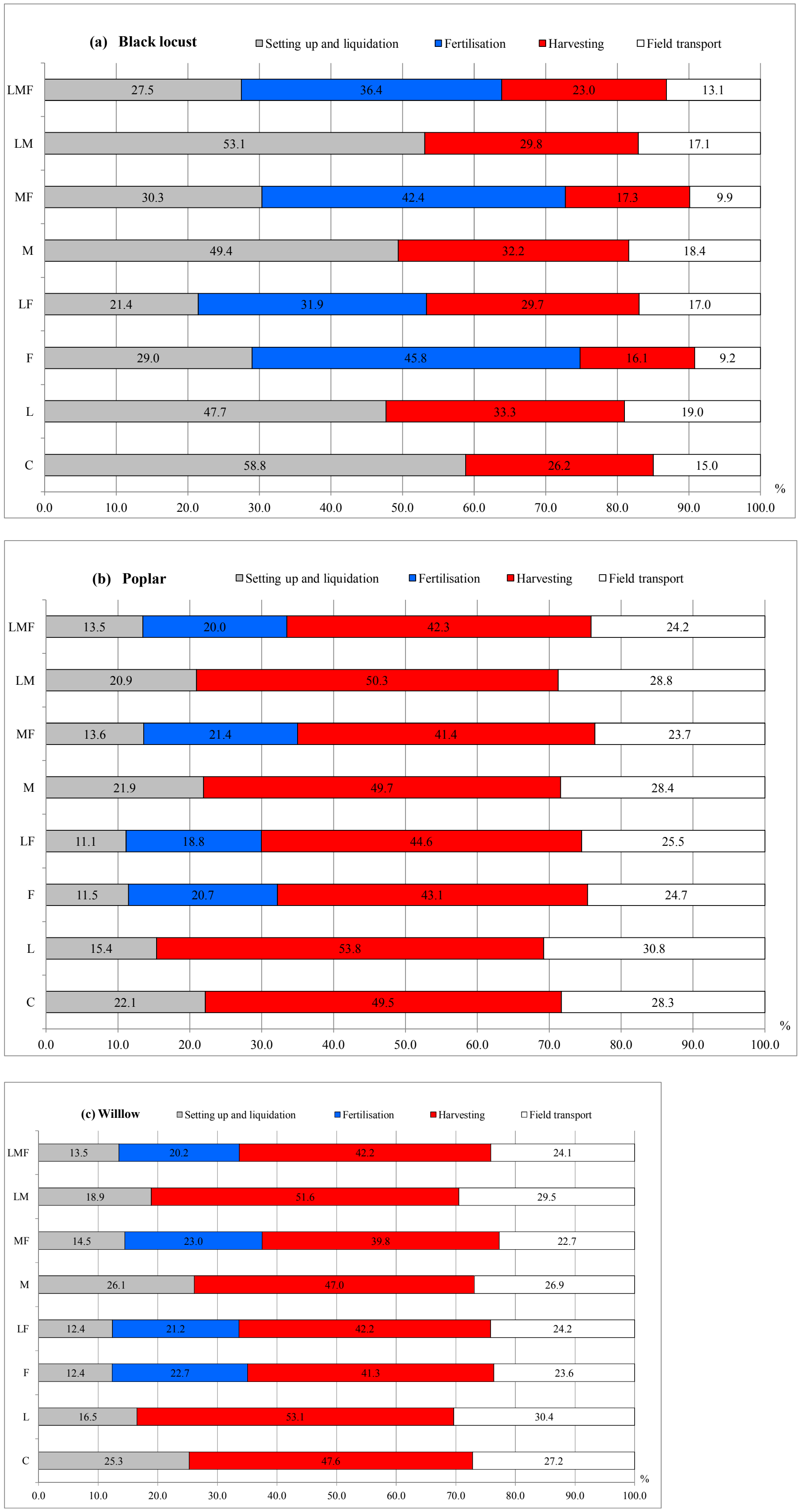

Fig. 3. Structure of energy input (%) for the production of black locust (a), poplar (b) and willow (c) chips in a four-year harvest rotation depending on the soil enrichment procedure by production operations.

Table 7
Energy efficiency analysis of biomass of black locust, poplar and willow in a four-year harvest rotation depending on the soil enrichment procedure.

Species	Soil enrichment procedure	Energy gain			Diesel fuel consumption			Energy intensity	
		GJ ha^{-1}	GJ ha^{-1} year^{-1}	Changes %, C = 100%	kg ha^{-1}	kg Mg^{-1} f.m.	kg Mg^{-1} d.m.	GJ Mg^{-1} f.m.	GJ Mg^{-1} d.m.
Black Locust	C	107.7	26.9	100	90.7	8.0	13.9	0.59	1.02
	L	181.3	45.3	168	125.3	6.7	11.5	0.47	0.80
	F	130.5	32.6	121	115.1	8.2	14.1	0.97	1.66
	LF	359.8	90.0	334	213.7	5.7	9.9	0.52	0.90
	M	180.6	45.2	168	120.7	6.5	11.2	0.48	0.83
	MF	151.3	37.8	140	124.6	7.6	13.2	0.89	1.55
	LM	164.6	41.1	153	117.9	6.9	11.9	0.52	0.89
	LMF	239.0	59.7	222	165.1	6.5	11.3	0.67	1.17
Poplar	C	354.6	88.6	100	246.7	5.0	11.3	0.31	0.71
	L	594.0	148.5	168	386.9	4.7	10.6	0.29	0.65
	F	590.5	147.6	167	397.6	4.8	10.8	0.36	0.81
	LF	673.7	168.4	190	449.1	4.7	10.7	0.35	0.79
	M	411.5	102.9	116	280.0	4.9	11.0	0.31	0.71
	MF	542.2	135.5	153	373.8	4.8	11.0	0.38	0.85
	LM	461.0	115.3	130	313.5	4.8	11.0	0.31	0.70
	LMF	598.0	149.5	169	407.4	4.8	10.9	0.37	0.83
Willow	C	336.3	84.1	100	212.6	5.2	10.4	0.33	0.66
	L	613.5	153.4	182	356.1	4.7	9.6	0.29	0.59
	F	593.1	148.3	176	355.4	4.9	9.8	0.38	0.75
	LF	640.5	160.1	190	387.5	4.9	9.9	0.37	0.74
	M	366.8	91.7	109	229.2	5.1	10.2	0.33	0.67
	MF	554.4	138.6	165	340.1	4.9	9.9	0.39	0.79
	LM	585.8	146.4	174	345.8	4.8	9.7	0.30	0.61
	LMF	669.7	167.4	199	403.5	4.8	9.8	0.37	0.75

i.e. 168.4 GJ ha^{-1} year^{-1}. A similar level of this parameter (669.7 GJ ha^{-1}) was achieved in the production of willow in the LMF object. In general, a higher energy gain was obtained in the production of willow and poplar than in the production of black locust. The highest index in the cultivation of black locust was achieved in the LF object (359.8 GJ ha^{-1}); however, it was at the same level as the lowest results for the control objects (C) in the production of poplar and willow.

It must also be emphasised that the energy gain in all three SRWC species under study was higher in each fertilisation option than in the controls (Table 7). For black locust, the methods of soil enrichment applied in this study resulted in an increase in energy gain from 21% up to 234% for the F and LF option, respectively, compared to C. For poplar, the smallest energy gain (16%) was achieved in option M, and the greatest was in LF (90%), compared to the C option for this species. These methods of soil enrichment, when used with willow, resulted in an increase in energy gain compared to C by 9–99%, for the M and LMF options, respectively.

It was found in other studies involving the production of willow chips in a three-year harvest rotation that the energy gain varied and depended on the cultivar, and it lays within a wide range from 125.2 to 697.0 GJ ha^{-1} [9]. Energy gain in willow cultivation in a three-year rotation in Sweden also amounted to about 600 GJ ha^{-1} [28]. Furthermore, the energy gain achieved in the production of poplar coppice with no fertilisation, in a four-year harvest rotation, at the end of the fourth cycle, amounted to 1419.8 GJ ha^{-1}, i.e. 88.7 GJ ha^{-1} year^{-1} [29], which is nearly the same as for poplar in the control object in this study. In another study with poplar coppice, with mineral fertilisation and watering, this parameter was much higher, 255 GJ ha^{-1} year^{-1} [16], whereas for black locust it was 181 GJ ha^{-1} year^{-1} [17].

Diesel fuel consumption calculated for 1 ha of a plantation was much higher in the production of willow and poplar chips than for black locust chips, which is a consequence of a different level of yield for the species (Table 7). The total consumption of diesel fuel in the production of black locust ranged between 90.7 and 213.7 kg ha^{-1}, whereas for willow and poplar it was 212.6–403.5 kg ha^{-1} and 246.7–449.1 kg ha^{-1}, respectively. On the other hand, diesel fuel consumption needed for the production of 1 tonne of fresh or dry biomass was lower for willow and poplar than for black locust. The lowest consumption of diesel fuel needed for the production of 1 tonne of fresh willow chips was recorded in object L (4.7 kg Mg^{-1} f.m. or 9.6 kg Mg^{-1} d.m.). The consumption of diesel fuel needed for the production of 1 tonne of dry willow chips was higher by 1.1% and 9.1% in objects LM and C, respectively. The lowest consumption of diesel fuel needed for the production of 1 tonne of fresh poplar chips was recorded in objects L and LF (4.7 kg Mg^{-1} f.m. or 10.6 kg Mg^{-1} d.m.). The consumption of diesel fuel needed for the production of 1 tonne of dry poplar chips was higher by 1.3% and 6.6% in objects LM and C, respectively. The lowest consumption of diesel fuel needed for the production of 1 tonne of fresh black locust chips was recorded in object LF (5.7 kg Mg^{-1} f.m. or 9.9 kg Mg^{-1} d.m.). The consumption of diesel fuel for the production of 1 tonne of dry black locust chips in the other objects was higher by 13.1% and 42.5%, in objects M and F, respectively.

The levels of consumption of diesel fuel needed for production of 1 tonne of fresh willow chips observed in other studies were similar to those recorded in this experiment for the highest-yielding cultivar (4.6 kg Mg^{-1} f.m.). The fuel consumption in the production of the other willow was higher by 3–53% [9]. Very low fuel consumption (3.0 l Mg^{-1}) of willow chips was recorded by Goglio et al. [30]. It was higher in studies conducted by Heller et al. [27] and by Gonzalez-Garcia et al. [31], 3.6 and 4.1 l Mg^{-1}, respectively. On the other hand, the consumption of fuel in the production of poplar biomass was higher (6.4–7.5 l Mg^{-1}) compared to the production of willow [32].

Likewise, the energy intensity of production of 1 tonne of chips was significantly differentiated by the species and methods of soil enrichment. The total amount of energy consumed for the production of 1 Mg of fresh chips was the lowest in the cultivation of willow and poplar in objects where lignin was applied (0.29 GJ Mg^{-1} f.m.). In the other objects where willow was cultivated, it was higher by 3.0% and 33.6% (in objects LM and MF,

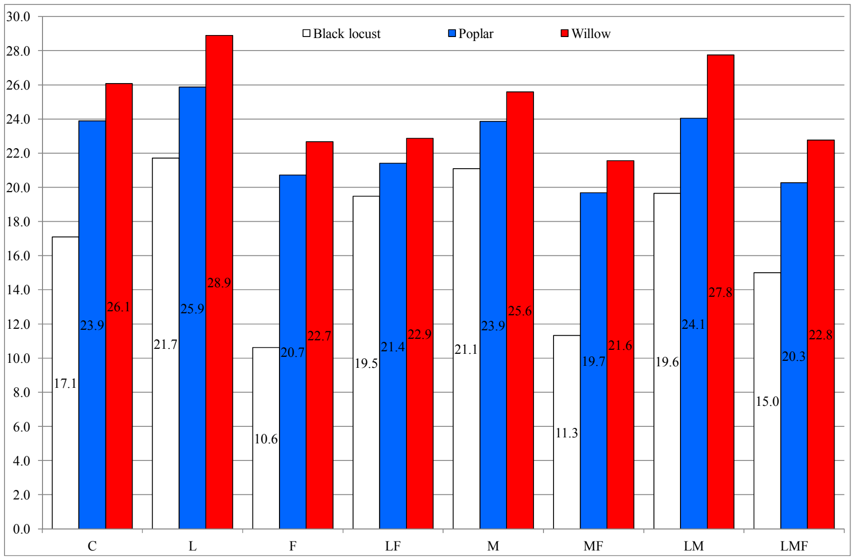

Fig. 4. Energy efficiency ratio for production of black locust, poplar and willow chips in a four-year harvest rotation depending on the soil enrichment procedure.

respectively) and it was higher for poplar cultivation by 7.0% and 30.1%, respectively (Table 7). As with willow and poplar, energy intensity in the production of fresh black locust chips was the lowest in object L (0.47 GJ Mg^{-1} f.m.). However, this value was considerably higher than for willow and poplar cultivated in object L. The highest value of energy intensity for black locust was recorded in object F (0.97 GJ Mg^{-1} f.m.). The lowest energy intensity found for the production of 1 Mg of dry chips of the SRWC under study was achieved in biomass production in objects in which lignin was applied (L), with the lowest recorded for willow (0.59 GJ Mg^{-1} d.m.), followed by poplar (0.65 GJ Mg^{-1} d.m.) and black locust (0.80 GJ Mg^{-1} d.m.). High energy input in the production of 1 Mg d m. of black locust was recorded in Italy (about 0.93 GJ) [17]. Even higher energy intensity ratios have been recorded for poplar cultivations in different rotations (from 1.06 to 1.09 GJ Mg^{-1} d.m.) [15]. Energy intensity in the production of willow chips in another study ranged from 0.35 GJ Mg^{-1} f.m. for cultivar UWM 006 to 0.77 GJ Mg^{-1} f.m. for UWM 155 [9]. A much lower energy intensity was achieved in harvesting 5-year-old poplar coppice [33].

The energy efficiency ratios for the production of black locust, poplar and willow chips in a four-year harvest rotation depending on the soil enrichment procedure are presented in Fig. 4. The energy efficiency ratios varied depending on the species and method of soil enrichment. In general, the highest energy efficiency (21.6 and 28.9) was recorded in the production of willow chips, in objects MF and L, respectively. The energy efficiency ratio for willow using different methods of soil enrichment was as follows: L–LM–C–M–LF–LMF–F–MF. The energy efficiency ratio in the production of poplar chips was 6.4–13.4% lower compared to the willow obtained in the same soil enrichment options. The sequence of energy efficiency ratios in relation to the soil enrichment options was the same as for willow. The energy efficiency ratio in the production of black locust chips ranged between 10.6 and 21.7 and it was lower by 14.8%–53.1% compared to willow obtained in the same soil enrichment options. The sequence of energy efficiency ratios for black locust in relation to the soil enrichment options was as follows: L–M–LM–LF–C–LMF–MF–F. Therefore, in terms of the energy efficiency ratio, production of chips was the most effective in objects in which soil was enriched with lignin alone, and it was the least effective when mineral fertilisation was used to enrich soil. Inclusion of mineral fertilisation in the production of willow and poplar resulted in a decrease in the energy efficiency ratio by 17–25% compared to the objects where lignin was applied; the decrease for black locust ranged from 10% to over 51%.

Considering the changes of energy efficiency ratio for the SRWC species under study in the controls compared to the soil enrichment options applied, it was shown that the greatest increase (26.9%) was achieved for black locust on the plot where lignin was used (Table 8). For black locust, an increase in energy efficiency ratio compared to C was also achieved for the LF, M and LM options. On the other hand, the energy efficiency ratio in the production of poplar and willow chips on the L plots was greater by 8.3% and 10.8% respectively, compared to C. An increase in the energy efficiency ratio for these species was also achieved on the LM plots, although on other plots where soil was enriched, it was lower than in C.

In other studies, the energy efficiency ratio for the production of willow chips in a three-year harvest rotation varied greatly depending on the cultivar and ranged within the period between 10.2 and 23.9, for cultivars UWM 006 and UWM 155, respectively [9]. The energy efficiency ratio of willow production found in other studies lay within a wide range from about a dozen to over 50 [27,34,35]. Similar levels of this parameter were recorded in the production of poplar coppice and black locust [15–17]. Much higher levels of energy ratio were achieved in harvesting 5-year-old poplar trees [33]. Varied energy ratios in the production of SRWC biomass result from differences in the preparation of the production site and

Table 8
Effect of soil enrichment options on (%) changes in the energy efficiency ratio compared to C plots, (C = 100%).

Soil enrichment procedure	Black locust	Poplar	Willow
C	100.0	100.0	100.0
L	126.9	108.3	110.8
F	62.1	86.8	86.9
LF	113.9	89.6	87.7
M	123.3	99.9	98.1
MF	66.2	82.4	82.7
LM	114.8	100.7	106.5
LMF	87.7	84.9	87.3

the use of mineral fertilisers and pesticides. Other important factors include species and cultivars, planting density, the harvest cycle and its technology, as well as the biomass yield.

4. Conclusions

The three species used in our study gave different biomass yield depending on the options of soil enrichment used. Varied energy input was made in different soil enrichment options and different energy output was obtained. However, the production of biomass from SRWC as a commodity must be a consequence of a logical sequence of technological processes and agrotechnical measures which help to obtain as high a yield of biomass and energy as possible with the lowest energy input. The production methods of willow, poplar and black locust biomass should be verified in future research and analyses in terms of energy-related features and to carry out more comprehensive analyses of cost and gain. Therefore, research findings should identify the optimum technological solutions for the production of SRWC biomass while a specific production technology which takes into account a given species/cultivar, agricultural measures, etc. should always have a positive energy efficiency ratio.

Our findings provide valuable information to producers of SRWC biomass in Europe and other regions around the world where climatic conditions are similar. However, they cannot be transposed to other conditions uncritically and directly (with no additional studies) because the energy intensity of the production process depends on multiple factors – soil-and-weather related, agrotechnical, organisational and human. The poorest results in this experiment were recorded for black locust, which deviates significantly in terms of energy gain and energy efficiency ratio from willow and poplar. The best energy efficiency ratio (28.9) was achieved for willow grown in the option in which lignin was used to enrich soil. The energy ratio in the production of poplar chips was 6.4–13.4% lower and was 14.8%–53.1% lower for black locust compared to willow chips obtained in the same soil enrichment options. The application of mineral fertilisation always decreased this parameter by 20–51%. On the other hand, the energy efficiency ratio in control objects was lower by only 8–21% compared to the highest values. Therefore, when commodity production of SRWC is carried out in large areas, when it is not possible to use by-products such as lignin, to enrich soil, it is better for the energy efficiency ratio not to use any enrichment measures than to apply, for example, mineral fertilisers. Moreover, we are convinced that both in Poland and in other countries with similar weather conditions, more attention should be devoted to the production of willow and poplar biomass as potentially more attractive sources of energy in a short-rotation harvest cycle compared to black locust.

Acknowledgement

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