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Research paper

Economic efficiency of willow, poplar and black locust production using different soil amendments

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ABSTRACT

Profitability of biomass production is the main condition to be fulfilled for farmers to be more interested in growing short rotation woody crops (SRWC). The aim of this study was to assess the cost and economic efficiency of production of chips from three SRWC species (willow, poplar, black locust) depending on the soil amendment method, biomass prices and the transportation distance to the end user. The economic analysis assessed the cost of dry chips and unit energy production, revenue, discounted pay-back period, net present value and internal rate of return.

In the base scenario the highest revenue 292 € ha^{-1} year^{-1} was found for willow amended with lignin. The best revenue for poplar (194 € ha^{-1} year^{-1}) was achieved when the crop was fertilised with mineral fertiliser and amended with lignin. No options for black locust were profitable. Other economic indices were the best in the production of willow as well. The change in the biomass price and transport distance influenced the revenue in the production of all species. Our study has indicated the importance of the right choice of species and method of soil amendment, as this determined the biomass yield and it had a great effect on the cost of chip production and the amount of revenue gained from such production.

1. Introduction

Solid biomass is usually derived from forests, the wood processing industry, from maintenance work on roads and urban vegetation, as well as from sorting waste. Agriculture is also an important source of biomass. This includes agricultural residues: cereal straw, corn stover, sugarcane bagasse, husk, etc., as well as plantations of perennial crops in the SRWC (short rotation woody crops, harvest rotations 1–5 years) and SRF (short rotation forestry harvest rotations more than 5 years) systems, such as: willow, poplar, black locust, eucalyptus and others [1–3]. Production of woody biomass on field plantations in the SRWC system is a challenge to agriculture in Europe [4–6] as well as in the USA and Canada [7–10]. However, the area on which SRWC are grown is still small compared to other agricultural crops. Willow is grown on the greatest area in Sweden – ca. 86 km^2 [11]. The area of SRWC plantations in Poland was 42 km^2 in 2005; it increased in subsequent years to reach 206 km^2 in 2015 [12]. The largest area in Poland is occupied by plantations of willow and poplar; the area of plantations of the latter species has been increasing in the recent years. Theoretically, the area of SRWC plantations can be increased because the area of land in Poland meeting the usability criteria for perennial energy and industrial crops (without being in competition or having a negative impact on production of food or fodders) is estimated to be 16 000 km^2 [13].

However, the profitability of biomass production is the main condition to be fulfilled for farmers to be more interested in growing SRWC. The economic efficiency of this kind of production – like any other – depends mainly on the demand and supply of this energy feedstock. Moreover, the profitability of SRWC biomass production strongly correlates with the crop yield. The dry matter yield of willow and poplar grown in experimental conditions on good soils and with good weather reached 30 Mg ha^{-1} year^{-1} [14,15]. However, it was much smaller in agricultural practice, where it has reached only 5–15 Mg ha^{-1} year^{-1} [16–19]. Furthermore, the yield of black locust did not exceed 10 Mg ha^{-1} year^{-1} even in experimental conditions [20,21]. Farmers set up SRWC plantations on soil of poorer quality, whose usability for food and fodder crops is lower, which is perfectly understandable and justified, because good quality soil is used for production of food crops. For example in Sweden about 60% of the farmers cultivated SRWC on soils that were of lower than average quality on their

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farms, 29% on average quality and 11% on better quality than the average quality soils on their farms [22].

Therefore, species, varieties, clones and methods of soil amendment must be sought which could increase the possibility of achieving satisfying SRWC biomass yield and economic gain even from soil of lower quality. Therefore, the aim of this study was (i) to assess the cost and economic efficiency of production of chips from three SRWC species (willow, poplar, black locust) depending on the soil amendment method, and (ii) to analyse the sensitivity of chip production for the options mentioned above, depending on changes in biomass prices and the chip transport distance to the end user.

2. Materials and methods

2.1. Field experiment

The study was based on a field experiment carried out in 2010–2013 on a poor soil site (Brunic Arenosol (Dystric)) formed from loose sand. The SRWC experiment was conducted in the north-east of Poland (53°59′ N, 21°04′ E) on land owned by the University of Warmia and Mazury in Olsztyn (UWM). Detailed data on the soil properties, weather conditions and the experimental procedure were presented in papers [21,23].

The first experimental factor were three SRWC species: willow (*Salix viminalis*, Żubr variety), poplar (*Populus nigra* x P. *Maximowiczii Henry* cv. Max-5) and black locust (*Robinia pseudoacacia* L.). All species were planted at a density of 11 111 ha^{-1}. Cuttings and seedlings were planted in twin-row design, which is a system frequently applied on SRWC plantations. The methods of soil amendment were the second factor. They included the following options: application of lignin as paper production waste, referred in this paper as 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 amendment (C). Lignin (L) as paper production waste was applied at 13.3 Mg ha^{-1} in spring 2010 before the experiment was set up. 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 mycorrhiza inoculation (M) was applied separately for each species in early September 2010. The inoculation in the form of liquid suspension at 30–35 cm^3 was applied under each plant with a manual applicator. The live mycorrhiza inoculum was purchased from a Polish company, which back then produced a wide variety of inocula and recommended their application in plantations of willow, poplar and black locust.

Mineral fertilisation (F) was applied before the beginning of the second growing season (2011). Phosphorus was applied at 30 kg ha^{-1} P_2O_5 as triple superphosphate, and potassium at 60 kg ha^{-1} K_2O as potassium salt. The first dose of nitrogen was applied as ammonium nitrate at 50 kg ha^{-1}, immediately before the plant growth started in 2011. The remaining amount of nitrogen was applied in the same form (40 kg ha^{-1}) in mid-June 2011.

The following procedures were identified in the study of SRWC biomass production study, (i) setting up the plantation: spraying with glyphosate (5 dm^3 ha^{-1}), winter ploughing, application of lignin, disking (2x), harrowing (2x), marking planting spots, manual planting, spraying with soil-applied herbicide (Guardian CompleteMix 664 SE, active substances: acetochlor and terbuthylazine, application rate 3.5 dm^3 ha^{-1}, no spraying was done on black locust), mechanical weeding (3x), manual application of mycorrhiza inoculation; (ii) running the plantation: mineral fertilisation, harvesting, field and road transport and liquidation of plantation. This study was based on a small-scale field trial conducted on 18 m^2 plots in three replications, from which specific biomass yield was obtained in various combinations of soil amendment. Subsequently, based on our study conducted on large-scale commercial plantations (there are ca. 60 ha of SRWC plantations owned by UWM) in regard to the efficiency of the tractors, machines, tools, etc., economic analyses were conducted in regard to all the production operations referred to the area of 1 ha. Data on the cost of harvest and transport were estimated on the basis of earlier study at a commercial plantation [24]. Detailed data on the analysed production technology and the types of equipment used in field operations are presented in Ref. [23].

2.2. Economic analysis

2.2.1. The cost of cultivation

An analysis of the economic efficiency of growing and producing chips of three SRWC species for different methods of soil amendment was presented with respect to the yield of dry biomass obtained in the first four-year harvest cycle. The total direct costs were divided into stages. The first stage covered setting up the plantation and the second covered its operation. The direct cost incurred for setting up and running a plantation in the first year of growth was divided into the 20-year long period of its operation (5 four-year cycles). Data acquired during the experiment were used to calculate the direct cost of individual production operations. Moreover, literature data, market data and the authors' data on the efficiency of agricultural equipment, purchase and the use of fertilisers and plant protection products, prices of seeding material and plantation liquidation after the end of its use were used. Biomass harvest was the next stage. Earlier studies by these authors [24] gave rise to the assumption that SRWC crops would be harvested in one stage with a Claas Jaguar 830 forage harvester. Chips were collected from the harvester with three units, each one consisting of a tractor and a transport trailer with a top element. Further parts of the analyses considered loading chips onto means of transport, transport of chips on vehicles in four distance options: 25, 50, 100 and 200 km (return journeys were also included). It was assumed that transport of fresh chips from a plantation to a conversion plant would be done in containers with a capacity of ca. 80 m^3 of chips in each, which makes about 25 tonnes of fresh chips per run. It was also assumed that an average monthly salary amounting to 990 €. With this data, the cost of human labour was found to amount to 5.63 € h^{-1}. Fresh chips of the SRWC species under study were valued, taking their market price during the period under study to be 4.85 € GJ^{-1}. Therefore, the calorific value of fresh SRWC chips obtained with different methods of soil amendment and the price of 1 GJ of energy contained in them were taken to calculate their value, and then recalculated on dry matter basis. Table 1 shows data from SRWC production and the cost used for the analyses.

2.2.2. Calculation

First, economic analyses were conducted for the base scenario (BS), which included production of chips of all species and all soil amendment options at the farm gate at the chips price of 4.85 € GJ^{-1}. Subsequently, sensitivity analyses were conducted for changes of biomass price (−25%, −10%, +10% and +25%) and distance of vehicle transport of chips to the end user (25 km, 50 km, 100 km and 200 km) compared to the base scenario.

The economic analysis included the following elements. A discounted cash flow analysis was conducted, which gave a discounted pay-back period (DPBP) for costs incurred for setting up, running and liquidation of a plantation of the SRWC under study in different amendments options. Annual cash flow was determined

Table 1
Data from SRWC production and the cost taken for the analyses.

Item	Unit	Value	Year of operation	Source data
Plantation lifespan	years	20	–	This study
Harvest cycle	years	4	–	This study
Number of harvests	–	5	–	This study
Planting density	cuttings ha^{-1}	11 111	–	This study
Interest rate	%	5	–	[6,24]
N fertiliser	€ kg^{-1}	0.89	–	This study, market purchase price
P fertiliser	€ kg^{-1}	0.78	–	This study, market purchase price
K fertiliser	€ kg^{-1}	0.60	–	This study, market purchase price
Lignin as fertiliser	€ kg^{-1}	0.01	–	This study, market purchase price
Glyphosate	€ l^{-1}	6.06	–	This study, market purchase price
Soil-applied herbicide[a]	€ l^{-1}	8.73	–	This study, market purchase price
Cuttings	€ ha^{-1}	404.13[b]; 1077.69[c]; 2020.67[d]	–	This study, market purchase price
Workforce	€ h^{-1}	5.63	–	Polish Central Statistical Office
Chips price	€ MWh^{-1}	17.46	–	This study and market price
Chips price	€ GJ^{-1}	4.85	–	This study and market price
Spraying	€ ha^{-1}	11.79	1	This study and [24]
Application of lignin	€ ha^{-1}	86.74	1	This study and [24]
Ploughing	€ ha^{-1}	59.74	1	This study and [24]
Diskinng	€ ha^{-1}	52.44	1	This study and [24]
Harrowing	€ ha^{-1}	37.82	1	This study and [24]
Marking planting spots	€ ha^{-1}	75.92	1	This study and [24]
Manual planting	€ ha^{-1}	125.00[b,c]; 416.66[d]	1	This study and [24]
Mechanical weeding	€ ha^{-1}	95.48	1	This study and [24]
Manual application of mycorrhiza inoculation	€ ha^{-1}	969.93	1	This study and [24]
Mineral fertilisation	€ ha^{-1}	55.20	2;5;9;13;17	This study and [24]
Land tax	€ ha^{-1}	23.04	1–20	This study and [24]
Liquidation of plantation	€ ha^{-1}	273.38	20	[24]
Harvesting	€ t^{-1} d.m.	24.25[b]; 27.13[c]; 20.71[d]	4;8;12;16;20	This study and [24]
Field transport	€ t^{-1} d.m.	10.60[b]; 11.88[c]; 9.07[d]	4;8;12;16;20	This study and [24]
Road transport 25 km, loading	€ t^{-1} d.m.	5.82	4;8;12;16;20	This study and [24]
Road transport 50 km, loading	€ t^{-1} d.m.	9.21	4;8;12;16;20	This study and [24]
Road transport 100 km, loading	€ t^{-1} d.m.	16.00	4;8;12;16;20	This study and [24]
Road transport 200 km, loading	€ t^{-1} d.m.	29.58	4;8;12;16;20	This study and [24]

[a] No spraying was done on black locust.
[b] For willow.
[c] For poplar.
[d] For black locust.

as the difference between the annual income and annual cost and subsequently discounted for each year.

In order to compare the profitability of SRWC production in the soil amendment options under analysis, net present value (NPV) and internal rate of return (IRR) were calculated. NPV was determined for each option from the formula:

$$NPV = \sum_{t=0}^{n} (1+r)^{-t} \cdot A_t$$

n = length of the calculation period (lifespan) in years
r = discount rate (5%)
t = time (year) at which a disbursement (or revenue) is made (or received)
A_t = size of payment

IRR was calculated from the formula:

$$\sum_{t=0}^{n} (1+i)^{-t} \cdot A_t = 0$$

An equivalent annual value (EAV) was also calculated from the model developed by Rosenqvist [25]. The model assumptions help to conduct a comparative analysis of production costs and its profitability by applying the net present value and the rent method. All production costs were discounted throughout the period of analysis, i.e. the period of a plantation use from setting it up to its liquidation (from the following formula).

$$EAV = \frac{r}{1-(1+r)^{-n}} \sum_{t=0}^{n} (1+r)^{-t} \cdot A_t$$

The discount rate of 5% was adopted in all calculations. The costs and revenue from SRWC production were spread over the growing period. In order to compare the results for SRWC to those for annual crops, the net present value (NPV) approach was adopted, in a manner similar to other studies [25–28], in which willow-production-related costs and revenue were converted into annual streams.

The calculations do not include direct subsidies offered to farmers as part of the common agricultural policy, production subsidies or cost of the land purchase.

3. Results and discussion

3.1. Base scenario

Table 2 present the experiment results for the base scenario (BS), 20 years of an SRWC plantation use in five consecutive harvest rotations, at the farm gate, for willow, poplar and black locust. The yield of SRWC varied for different species and methods of soil amendment and ranged from 1.63 to 10.49 Mg ha^{-1} $year^{-1}$ d.m., for black locust grown on the control plot (C) and poplar grown on the plot where lignin was used in combination with mineral fertilisation (LF), respectively. All the species gave the lowest yield on

Table 2
Results for willow, poplar and black locust chip production for different soil amendment at the farm gate (Base Scenario - BS).

Soil amendment	Lower heating value (GJ Mg^{-1} f.m.) [21]	Yield (Mg ha^{-1} $year^{-1}$ d.m.)	Price (€ Mg^{-1} d.m.)	Costs (€ Mg^{-1} d.m.)	Costs (€ GJ^{-1})	Sum of costs (€ ha^{-1} $year^{-1}$)	Revenue (€ ha^{-1} $year^{-1}$)	NPV (€)	IRR (%)
Willow									
C	8.51	5.10	83.2	56.5	2.9	267.2	126.3	1653.3	19.9
L	8.44	9.32	82.6	48.9	2.5	423.0	291.7	3817.0	29.1
F	8.51	9.08	82.8	52.9	2.7	446.0	252.1	3298.2	28.3
M	8.46	5.60	82.8	68.8	3.5	357.6	72.7	950.9	10.0
LF	8.40	9.83	82.7	54.0	2.8	492.4	261.8	3425.9	25.3
MF	8.41	8.55	82.5	63.7	3.3	505.1	148.8	1947.2	13.8
LM	8.35	8.95	82.3	58.6	3.0	486.9	197.0	2578.3	15.8
LMF	8.37	10.30	82.5	60.9	3.1	582.3	206.0	2695.9	15.6
Poplar									
C	7.48	5.48	82.0	69.3	3.5	352.1	64.5	844.4	10.3
L	7.46	9.16	81.9	59.4	3.0	504.7	191.2	2501.8	16.9
F	7.45	9.21	81.6	62.8	3.2	536.1	161.3	2111.1	15.8
M	7.46	6.38	81.6	77.5	4.0	458.9	24.2	316.9	6.3
LF	7.45	10.49	81.7	61.8	3.2	601.6	193.9	2537.8	16.3
MF	7.38	8.51	81.4	72.9	3.7	575.8	66.9	875.9	8.5
LM	7.42	7.15	81.6	76.4	3.9	506.7	34.8	454.9	6.7
LMF	7.43	9.35	81.5	73.2	3.7	634.8	72.5	948.1	8.3
Black locust									
C	10.10	1.63	84.7	191.5	9.8	290.5	−162.1	−2120.5	negative
L	10.12	2.72	84.7	134.3	6.9	339.4	−125.3	−1640.1	negative
F	10.27	2.04	85.5	185.1	9.5	350.4	−188.6	−2468.3	negative
M	10.16	2.7	85.5	157.6	8.1	394.1	−179.7	−2351.9	negative
LF	10.19	5.4	85.1	92.3	4.7	462.2	−35.7	−466.6	3.3
MF	10.12	2.36	85.4	198.3	10.2	433.9	−247.0	−3232.5	negative
LM	10.21	2.47	85.2	177.3	9.1	406.4	−211.2	−2763.0	negative
LMF	10.12	3.65	85.1	144.3	7.4	488.5	−200.4	−2622.8	negative

control plots, and the methods of soil amendment used affected a yield increase differently. Poplar and black locust gave the highest yield on LF plots and willow on the plot where lignin was applied in combination with mycorrhiza and mineral fertilisation (LMF). It must be emphasised that the findings of this study may not be applicable to other sites, because of other soil, climatic, logistic, etc. conditions.

The cost of SRWC chip production varied for different methods of soil amendment and different levels of yield of the species under study. The lowest cost of chip production was noted for all the species at the control plots (C), where no fertilisation was applied; it ranged from 267 to 352 € ha^{-1} $year^{-1}$, for willow and poplar, respectively (Table 2). It increased at plots where various methods of soil amendment were applied and it was the highest where lignin, mycorrhiza and mineral fertilisation were used in combination (LMF); it was the highest for poplar 635 € ha^{-1} $year^{-1}$. Moreover, the yield of SRWC species affected the cost of production, because higher yielding species (willow and poplar) generated higher chip production costs (per hectare, but lower per tonne d.m.), which arose mainly from the crop harvest costs. On the other hand, willow and poplar consumed the costs incurred for setting up the plantation and soil amendment definitely more effectively compared to black locust. Therefore, methods of reducing unit costs of SRWC biomass production should be sought by the selection of species, varieties and by optimising technologies of crop cultivation and harvesting. This was demonstrated in earlier studies [24] in which the cost of willow production in the same habitat and technological conditions ranged from 374 to 1219 € ha^{-1} $year^{-1}$, because of varied yield of the grown varieties. Other studies showed that an increase in yield by 18% can reduce the unit cost of biomass supply to the end user by 13% [29]. It was also found that the choice of the optimum cultivation technology and using wastewater and sludge as fertilisers on a willow plantation can considerably reduce the unit cost of chip production [30–32].

The diversity of the unit cost of biomass production in our study was very wide. In general, the lowest cost of production of 1 Mg d.m. of chips was incurred for willow; it ranged from 48.9 to 68.8 € Mg^{-1}, for the plots where only lignin (L) and only mycorrhiza (M) were applied (Table 2). The cost of poplar chip production for the same soil amendment options was higher by 13–30% than for willow chips. On the other hand, the production costs of black locust chips were higher than willow by 71–250%, for the same options of soil amendment. In the cultivation of willow and poplar, only the application of lignin and mineral fertilisers and these two in combination reduced the unit cost per Mg d.m. (by 4–13%) compared to the control plot, whereas the application of the other options increased the cost (by 4–22%). On the other hand, the unit cost of the production of black locust chips at the control plot (C) was high (191.5 € Mg^{-1} d.m.) and it was higher by 4% only in the option with mycorrhiza and mineral fertilisation in combination; they were lower (by 3–52%) in all the others. It was also demonstrated in other studies that the production costs of willow chips vary, amounting to 57 € Mg^{-1} d.m. for the highest-yielding variety and it was 56% higher for the lowest-yielding variety [24].

Similar relationships for the cost of producing 1 Mg d.m. of chips between species and methods of soil amendment have also been shown in analyses of the production costs of 1 GJ of energy. The lowest cost of energy production from the species under study was achieved for willow (range 2.5–3.5 € GJ^{-1}, for the L and M options, respectively) (Table 2). The cost of production of an energy unit from poplar (3.0–4.0 € GJ^{-1}) was higher by 12–21% and from black locust (4.7–10.2 € GJ^{-1}) was higher by 68–252% compared to willow for the same options of soil amendment. The production cost of an energy unit from willow grown at a higher density and in 3-year harvest cycles ranged from 3.4 to 5.7 € GJ^{-1} and depended on the variety and planting density [24]. In other studies for Poland, the cost of production of 1 GJ in willow biomass depending on the cultivation scenario ranged from 2.4 to 3.3 € GJ^{-1} [33]. It was also shown in a review paper that the cost of the production of willow and poplar biomass on 23 SRWC plantations varied greatly (0.8–5 € GJ^{-1}) depending on the species, methodology and time of the study [34].

The price of chips obtained from the SRWC species under study depended on their calorific value and was differentiated by the species more than it was by the soil amendment method. The highest price was calculated for black locust chips –85.2 € Mg^{-1} on average (Table 2). The average price of willow chips was lower by 2.9%, whereas that of poplar chips was lower by 4.1% compared to black locust.

The price of chips and the yield significantly differentiated the revenue obtained from a plantation of SRWC in various options of soil amendment. The lowest revenue was achieved for willow; at the control plot (C) (126.3 € ha^{-1} $year^{-1}$) and the highest value (291.7 € ha^{-1} $year^{-1}$) was achieved at the L plot (Table 2). The revenue from willow cultivation was higher by 18–107% in the other options of soil amendment compared to C, except at the one where mycorrhiza was applied, in which the revenue was lower by 42% compared to C. Similar relationships between the soil amendment methods were noted in growing poplar, where the revenue was lower only at the M and LM plots and it was higher for the other soil amendment options compared to C. The highest revenue in poplar production (193.9 € ha^{-1} $year^{-1}$) was achieved at the LF plot and it was higher by 201% compared to C. However, the revenue achieved for poplar was equal to 18%–64% of the values achieved for willow in the same soil amendment options. Furthermore, the production of black locust chips in a 4-year harvest cycle proved to be unprofitable in all the cultivation options. The cultivation of black locust in the SRC (8 year rotation) and SRF (15-year rotation) system was not profitable either, because the profit gained amounted to −184 and −172 € ha^{-1} $year^{-1}$ [35].

The revenue obtained from growing SRWC in our study was reflected in the net present value (NPV). In the willow cultivation, the index was the highest (3817 € ha^{-1}) in the L option, and in the poplar cultivation – in the LF option (2538 € ha^{-1}) (Table 2). Both in the production of willow and poplar, using lignin alone or lignin with mineral fertilisation, caused the NPV to increase 2- and 3-fold, respectively. On the other hand, using mycorrhiza alone resulted in a 1.7–2.7-fold decrease in the NPV than in the C plots, for willow and poplar, respectively. Therefore, in the other combinations in which mycorrhiza was applied, NPV was slightly higher than in C plots and it was lower in poplar in the LM option. Furthermore, NPV was negative in all the options of soil amendment in the production of black locust.

The internal rate of return was higher than the discount rate for all the amendment options in willow and poplar cultivation (Table 2). Production of black locust could be regarded as profitable only in the LF option, with an internal rate of return of 3.3%.

Fig. 1 shows the discounted cash flows of SRWC chip production depending on the method of soil amendment in five consecutive 4-year harvest cycles (20 years of the plantation use). The shortest discounted period of return after the first harvest (the 4th year of the plantation use) was achieved for willow production in options L, F and LF (Fig. 1a). Subsequently, after the second harvest (8th year), the discounted period of return was achieved for the other options of willow production, except for the application of mycorrhiza (M) and for the production of poplar in options L, F and LF (Fig. 1a and b). The discounted rate of return was achieved after 12 years for all willow production options and at the C plot in poplar production. Return of outlay for poplar production in the other options of soil amendment was not achieved until the 4th harvest

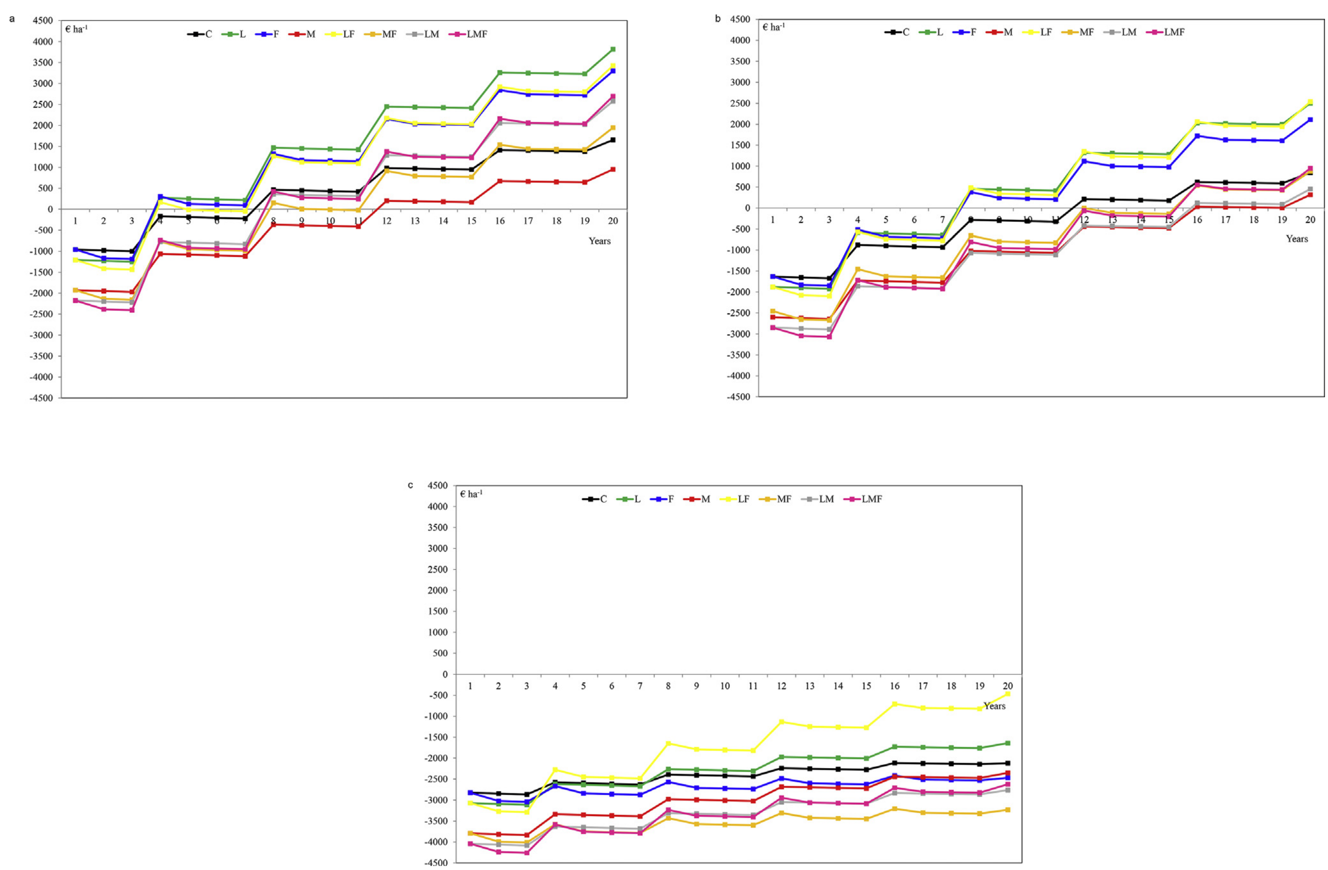

Fig. 1. Discounted cash flows of SRWC chip production depending on the soil amendment option in five consecutive 4-year harvest rotations for (a) willow, (b) poplar, (c) black locust. The methods of soil amendment: lignin (L), mineral fertilisation (F), inoculation with mycorrhiza (M), lignin + mineral fertilisation (LF), mycorrhiza + mineral fertilisation (MF), lignin + mycorrhiza (LM), lignin + mycorrhiza + mineral fertilisation (LMF), control, with no soil enrichment (C).

rotation (Fig. 1b). Furthermore, the return of outlays was not achieved during the 20 years of use of a black locust plantation in any of the chip production options (Fig. 1c). The production efficiency of woody biomass as energy feedstock in the SRWC system can vary. The analysis has shown that of the 37 studies, 43% reported economic viability in comparison to a reference system, whereas 19% stated economic disadvantages; furthermore, 38% reported mixed results, depending on the assumptions made [6]. It has also been shown that the production of SRWC (willow and poplar) can only be financially feasible if a number of additional conditions regarding biomass price, yield and government support were fulfilled [34].

3.2. Revenue sensitivity analysis

3.2.1. Transport distance of wood chips

The sensitivity analysis for the effect of the chip transport distance on revenue was conducted for four distance variants: 25, 50, 100 and 200 km. Obviously, an increase in the transport distance significantly reduced the final revenue in all the species (Fig. 2). When chips were transported for 25 km, the revenue was lower by 17–42% for the L and M options, respectively, compared to the base scenario (Fig. 2a). A further increase in the transport distance for willow chips to 50 km resulted in a revenue reduction by 28–66%. Furthermore, when willow chips were transported for 100 km in the mycorrhiza option (M), their production was no longer profitable. A positive revenue was achieved only for the L and F options when the transport distance was the longest (200 km); willow production generated losses in the other options. The production of poplar chips was not profitable for the M and LM variants even at the shortest distance (Fig. 2b). An increase in the transport distance for poplar chips resulted in the further production options for this species being unprofitable. The production of poplar was not profitable in any of the soil amendment options for the transport distance of 200 km. Furthermore, an increase in the transport distance in the case of black locust increased the loss incurred already in the base scenario (Fig. 2c). We also demonstrated [24] that a change in the transport distance for willow chips had a considerable effect on revenue. Extending the transport distance from 50 to 100 km reduced the revenue by 28–73%. When the transport distance increased further to 200 km, a revenue was achieved only for the two highest-yielding varieties and a loss was incurred for the other varieties.

3.2.2. Price of wood chips

A sensitivity analysis for an effect of SRWC chip price on revenue was conducted with the assumption that it would be lower or higher by 10% and 25% compared to the chip price in the base scenario. Reduction of the chip price by 10% reduced the revenue by 25–59% for the L and M options, respectively, compared to the base scenario (Fig. 3a). Nevertheless, willow cultivation was still profitable in all soil amendment options. However, when the price of willow chips decreased by 25%, their production was not profitable in the M and MF options. The highest revenue in this variant was achieved for willow amended with lignin (113 € ha^{-1} $year^{-1}$). Furthermore, when the price of willow chips increased by 25%, the

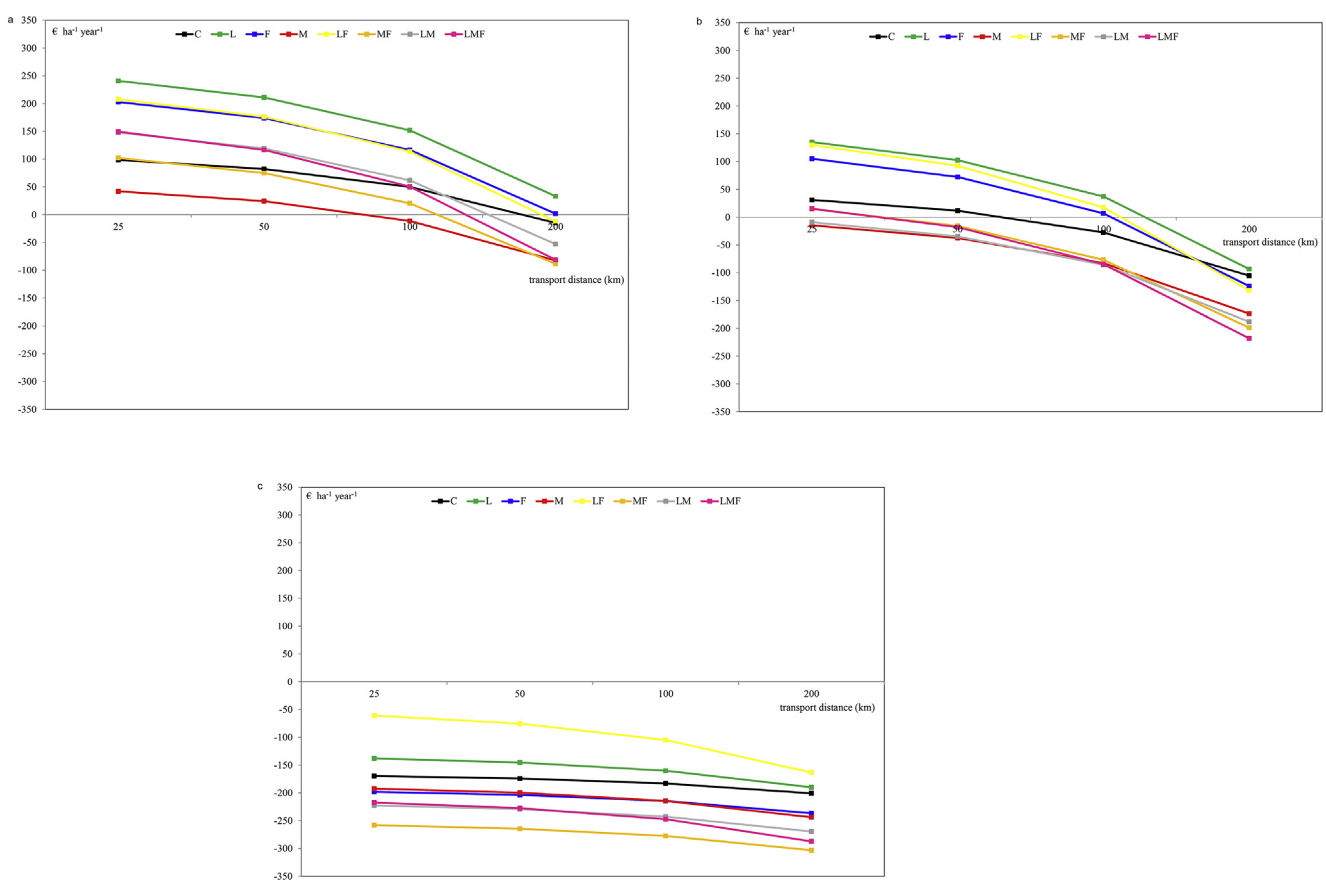

Fig. 2. The effect of transport distance (25, 50, 10, 200 km) for SRWC chips on revenue, for (a) willow, (b) poplar, (c) black locust depending on the soil amendment option: lignin (L), mineral fertilisation (F), inoculation with mycorrhiza (M), lignin + mineral fertilisation (LF), mycorrhiza + mineral fertilisation (MF), lignin + mycorrhiza (LM), lignin + mycorrhiza + mineral fertilisation (LMF), control, with no soil enrichment (C).

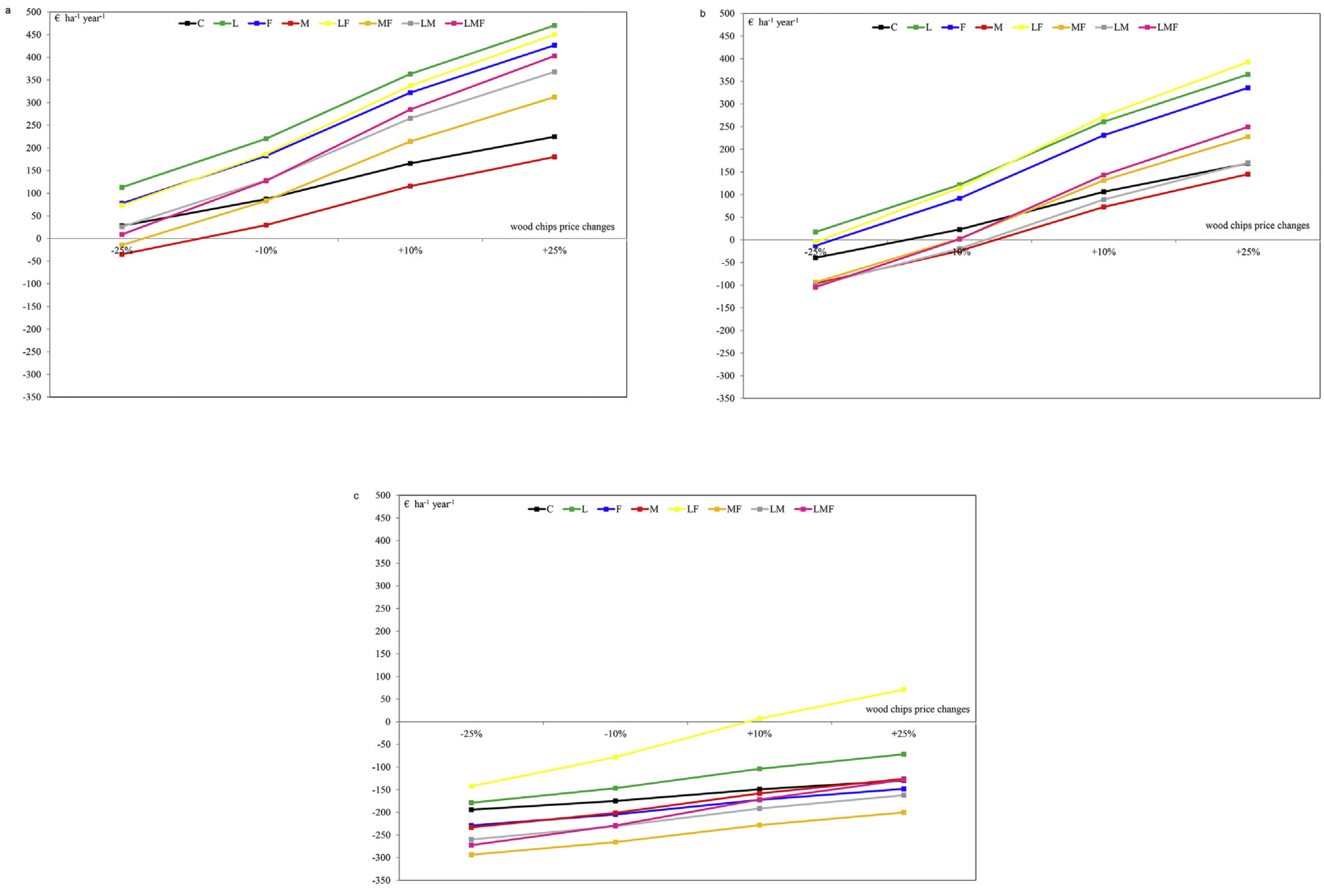

Fig. 3. The effect of changes in the price of SRWC chips (−25%, −10%, +10%, +25%) on revenue, for (a) willow, (b) poplar, (c) black locust depending on the soil amendment option: lignin (L), mineral fertilisation (F), inoculation with mycorrhiza (M), lignin + mineral fertilisation (LF), mycorrhiza + mineral fertilisation (MF), lignin + mycorrhiza (LM), lignin + mycorrhiza + mineral fertilisation (LMF), control, with no soil enrichment (C).

revenue in the same cultivation option was also the highest and amounted to 470 € ha^{-1} $year^{-1}$. When the chip price increased by 25% and 10%, the revenue was higher by 61–148% and 25–59%, for willow grown in the L and M options, respectively. The weakest reaction to changes of biomass prices were observed in the control plot, because of a low yield of willow chips in this cultivation option.

Reduction of the poplar chip price had a more adverse effect on revenue obtained from its cultivation than was the case for willow. When the poplar chip price was decreased by 10%, a positive effect was not achieved in as many as four soil amendment variants and the revenue for the others was lower by 36–64% compared to the base scenario (Fig. 3b). Furthermore, when the price of poplar chips was reduced by 25%, a profit was achieved only for the variant in which soil was amended with lignin (L), but it was lower by 91% compared to the base scenario. A loss was incurred in the other cultivation variants. An increase in the price of poplar chips by 10% and 25% resulted in a large increase in revenue, depending on the soil amendment option (by 36–200% and 91–499%, respectively). Therefore, production of the species was profitable in all the cultivation options, with the highest revenue (393 € ha^{-1} $year^{-1}$) achieved in the LF variant. Decreasing the price of black locust chips further increased the loss incurred in its production (Fig. 3c). When the price increased by 10% and 25%, a profit was achieved only in the LF variant, but it amounted only to 7 and 71 € ha^{-1} $year^{-1}$, respectively.

Similar effects of biomass prices on revenue from SRWC cultivation have been observed in other studies [24]. Compared to the base scenario, when the price of willow chips increased by 10%, the profit earned from cultivation of different varieties increased by 33–92%, with the highest achieved for the willow UWM 006 (713 € ha^{-1} $year^{-1}$). Moreover, it was found that a change in the biomass price had a definitely greater and more beneficial effect on the final revenue compared to a change in the yield level. A greater effect of changes of biomass price than of the yield on the final gross margin has also been shown in other studies [33].

3.2.3. Transport distance and wood chip price

An analysis of the effect of the transport distance and the chip price on revenue gained from SRWC production revealed more complex relationships. A decrease in the chip price by 10% compared to the base scenario made willow production profitable in all soil amendment options and the shortest transport distance of 25 km (Fig. 4a). When the transport distance for willow chips increased to 50 km, a loss was incurred only for soil amendment with mycorrhiza. The highest revenue in willow production with a decrease in biomass price by 10% was higher by over 100 € ha^{-1} $year^{-1}$ than in poplar production. However, a decrease in the chip price by 10% compared to the base scenario made poplar production profitable only at the transport distances of 25 and 50 km, in the L, F and LF soil amendment variants (Fig. 4b). Poplar production was not profitable for the other variants of a biomass price decrease by 10%. The situation was even worse when the biomass price decreased by 25%, because production of willow was profitable only at the two shortest transport distances (Fig. 4a) and the poplar production was not profitable in this variant (Fig. 4b).

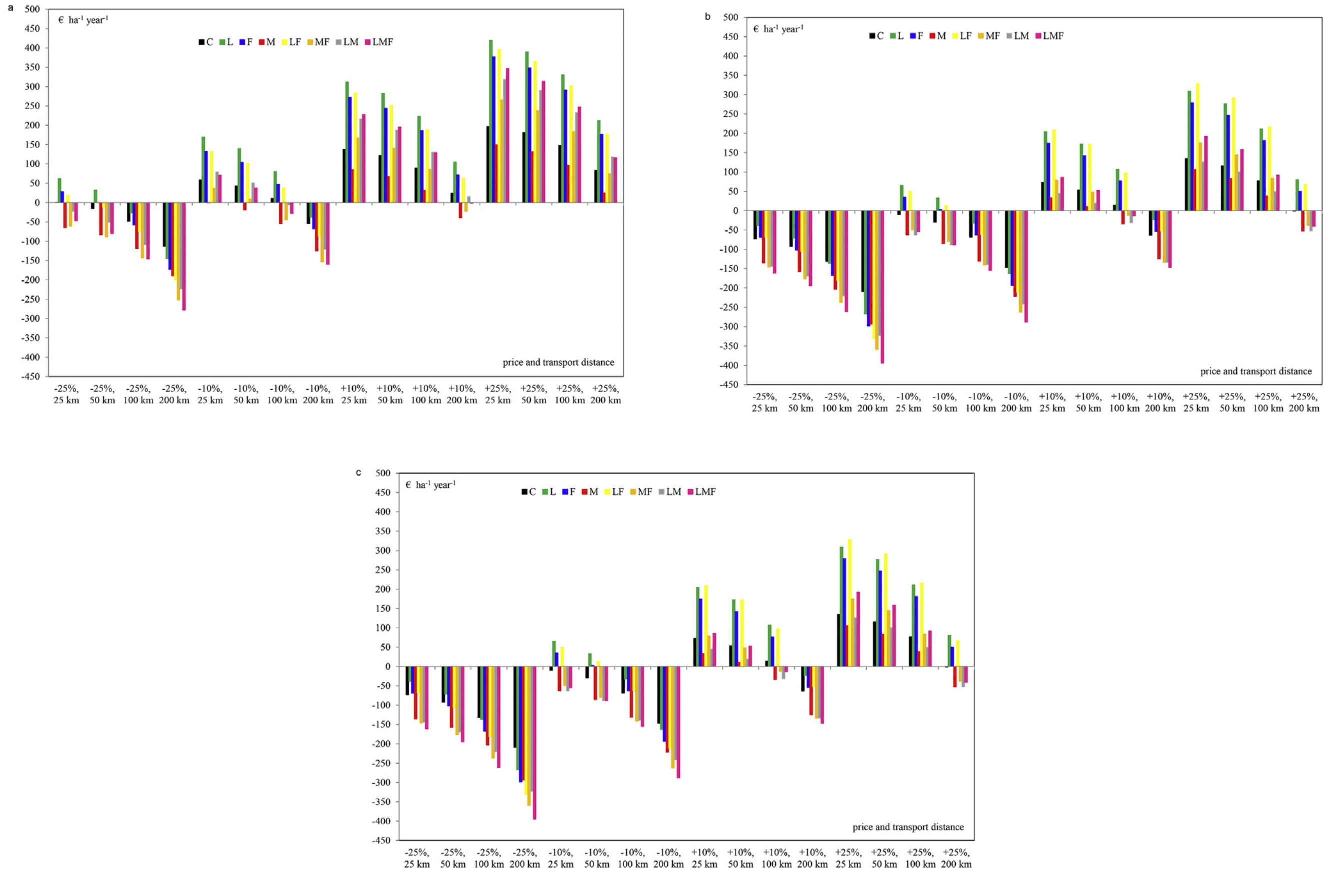

Fig. 4. The effect of changes in the price and transport distance for SRWC chips on revenue, for (a) willow, (b) poplar, (c) black locust depending on the soil amendment option: lignin (L), mineral fertilisation (F), inoculation with mycorrhiza (M), lignin + mineral fertilisation (LF), mycorrhiza + mineral fertilisation (MF), lignin + mycorrhiza (LM), lignin + mycorrhiza + mineral fertilisation (LMF), control, with no soil enrichment (C).

An increase in the biomass prices by 10% helped to achieve a positive revenue from willow production at the transport distance of 25, 50 and 100 km in all the soil amendment options and in most of them when the transport distance was the longest (Fig. 4a). Production of poplar was profitable in all the soil amendment options only at the two shorter transport distances and it brought no profit at the longest transport distance (Fig. 4b). The highest revenue in this price option amounted to 312 € ha^{-1} $year^{-1}$ for willow and to 209 € ha^{-1} $year^{-1}$ for poplar. An increase in the biomass price by 25% helped to achieve a positive revenue from willow production for all transport distances and all soil amendment options (Fig. 4a). The highest revenue for willow (420 € ha^{-1} $year^{-1}$) was achieved at the shortest transport distance when lignin was used as amendment. An increase in the poplar biomass prices by 25% helped to achieve a positive revenue for all the soil amendment options only for the first three transport distances. Production of poplar was profitable with the longest transport distance only for the L, F and LF variants (Fig. 4b). The highest revenue for poplar (329 € ha^{-1} $year^{-1}$) was achieved at the shortest transport distance when lignin and mineral fertilisers were used in combination. Furthermore, production of black locust chips brought a positive revenue only when the biomass price increased by 25% and at the transport distance of 25 and 50 km, when lignin and mineral fertilisers were used in combination (Fig. 4c). However, the revenue amounted only to 46 € ha^{-1} $year^{-1}$ at the most.

These analyses have shown that the selection of an SRWC species in biomass production in 4-year harvest cycles, the yield, chip price and distance of chip transport to the end user are the basic factors that affect the profitability of this kind of production for energy production. Other studies have also shown that the main factors that affect the efficiency of SRWC chips production include the biomass price offered on the energy market, harvest cycle, the yield, method of biomass harvest and the transport distance [3,24,36–42]. Due to the large number of such factors, including those beyond the control of a producer (such as: biomass price, transport distance), production of SRWC could be unprofitable or unattractive compared to the traditional agricultural crops. Studies [10,43,44] show that much better economic effects can be achieved when SRWC biomass is used directly by farmers (producers) to meet their own needs, for example, to produce heat (utility hot water and central heating water) for residential and farm buildings.

4. Conclusions

Economic efficiency of the production of SRWC chips in a 4-year harvest rotation was strongly differentiated by species (willow, poplar, black locust) and methods of soil amendment. Our study has indicated the importance of the right choice of species and method of soil amendment, as this determined the biomass yield and it had a great effect on the cost of chip production and the amount of revenue gained from such production. The best economic indices were achieved in the production of willow. The cost of producing 1 Mg of willow chips and of 1 GJ was lower compared to such costs for poplar and black locust incurred for the same soil amendment variants. Higher revenue was achieved for willow than for poplar in all the variants of soil amendment. It was also found for these two species that the methods of soil amendment applied (especially lignin) gave positive economic effects compared to the control, except for the application of mycorrhiza. However, the production of black locust chips proved to be unprofitable in all soil amendment options. The best discounted period of return after the first harvest (the 4th year of the plantation use) was achieved for willow production in options L, F and LF.

The change in the biomass price had a huge effect on the revenue in the production of all species. When the price decreased by 25%, only the production of willow remained profitable and this was only in some variants of soil amendment. Furthermore, when the biomass price increased by 25%, willow grown on soil amended with lignin gave the highest revenue (470 € ha^{-1} $year^{-1}$) of all the production options under study. An increase in the transport distance for willow and poplar chips significantly reduced the final revenue. In the longest option (200 km) poplar production was not profitable while willow production still gave a positive effect in variants L and F.

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