Energy 113 (2016) 748–761

Contents lists available at ScienceDirect

Energy

journal homepage: www.elsevier.com/locate/energy

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

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A R T I C L E I N F O

Article history:
Received 18 May 2016
Received in revised form
15 July 2016
Accepted 20 July 2016

Keywords:
Willow
Poplar
Black locust
Energy balance
Energy efficiency ratio
North-eastern Poland

A B S T R A C T

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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http://dx.doi.org/10.1016/j.energy.2016.07.098
0360-5442/

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