Energy and economic sustainability of woodchip production by black locust (Robinia pseudoacacia L.) plantations in Italy

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Abstract

Growing demand for energy has led to a rise in the price of fossil oil and an increased rate of depletion of fossil resources. This situation has generated a strong interest in the use of biofuel, and many studies have been undertaken on the worldwide potential for biofuel. Among all renewable energy sources, biomass could contribute to meeting the EU's renewable energy targets in 2020, especially short rotation coppice (SRC). In order to evaluate the energy and economic sustainability of woodchip production by black locust SRC, an *ad hoc* study was undertaken and a specific calculation model was developed. Data were collected in a black locust SRC plantation site in North West Italy during the period 2006 to 2012. This involved an SRC duration of six years and a biomass (10 Mg ha^{-1} DM per year) harvest at the end of a cycle (six years). The results indicated that black locust plantations are very desirable from an energy point of view since the output/input ratio results are higher than 20. Unfortunately, the results are not so positive from an economic point of view. In fact, in order to obtain economic sustainability for woodchip production, the biomass price should be at least €103 Mg^{-1} DM. Consequently, woodchip production by black locust SRC is only possible with economic support for production and with optimisation of agricultural labour and biomass production.

Keywords

Short rotation coppice; black locust; biomass; woodchip; production costs; energy consumption

1. Introduction

Growing demand for energy has led to a rise in the price of fossil fuel and an increased rate of depletion of fossil resources [1]. This situation has generated a strong interest in biofuel use, which many governments support through subsidies, tax-exemptions and other incentives [2]. Many studies have been undertaken on the worldwide potential for biofuel. The US Department of Energy recently released a major update regarding its biomass energy supply potential over the next two decades [3]. Fischer et al. [4] conducted a similar study on the European potential for biofuel production, while other authors have looked at biofuel deployment for sub regions within Europe [5-6] and Asia [7–10].

Among all renewable energy sources, biomass could contribute to meeting the EU's renewable energy targets in 2020 [11–12], especially short rotation coppice [13]. There has been increased interest in biofuels in Italy in the last 10 years. In fact, crop cultivation for biomass production has been included in the cultural plans of several farms, particularly in Northern Italy; farmers take advantage of the low input requirement and the added possibility of exploiting reserved areas [14].

At present there are two different methods of cultivation: very short rotation coppice (vSRC), with very high density, from 5500 to 6700 plants ha^{-1} and harvested with a rotation period of one to three years, and short rotation coppice (SRC) with a high density from 1000 to 2000 plants ha^{-1} and harvested with a rotation period of five to seven years [15-16]. In Europe, farmers generally prefer the vSRC cultivation model [17-21]; however, in Italy, farmers prefer the SRC method because it improves biomass quality (high calorific value) and market opportunity as a result of a better wood/bark ratio and the possible production of different wood types [22-25]. Furthermore, it is also preferred because, in rural development plans for the main regions of Northern Italy, the establishment of this cultural model is financed by the local government.

Fast-growing wood crops such as willows, poplars, and black locust have traditionally been considered to produce local fuel wood, wood material, and, more recently, energy [26-27]. These crops have potential for feedstock because of high yields, low costs, opportunities for use on lower-quality lands and biodiversity support at the local level. Most of the studies carried out in Italy to date have focused only on woodchip production from poplar [28-31], and willow [32-33] SRC, as they are spread more throughout the territory; few studies have yet examined black locust (Robinia pseudoacacia L.) [34-35].

In order to improve knowledge about woodchip production by black locust plantations, economic and energy evaluations were performed for short rotation coppice of black locust.

2. Materials and methods

A series of data was collected in a black locust SRC plantation near the experimental farm "MEZZI" of CRA-PLF, close to Casale Monferrato (AL) in the North West of Italy, during the period from 2006 to 2012. Because of the soil characteristics of the land chosen for the trials, a black locust of Italian origin was planted [36]. All the cultural operations for black locust cultivation were analysed. The working time and manpower requirements were recorded in the field, according to Magagnotti and Spinelli (2012) [37].
The developed model allowed the determination of manpower and energy requirements, as well as costs, regarding different biomass production. The model considered a continuous black locust SRC plantation: the whole acreage was divided into different "modules", each corresponding to one year of the crop cycle, thereby enabling all costs to be considered on an annual basis. For the economic and energy evaluations, a six-year rotation was considered, with harvesting carried out at the end of the cycle and with a starting plant density of 1100 per hectare, with a 3.00 × 3.00 m spacing and a mean production of 10 Mg ha^{-1}DM per year [36, 38]. For all post-emergence treatment, traditional 4RM tractors were used, with a maximum

width of 2.2 m. For planting the nursery and the black locust SRC, the soil was prepared by ploughing at a depth of 0.4 m after seed bed fertilisation – 500 kg ha^{-1} of PK 8-24. Secondary tillage was carried out with two harrowing interventions, while for rooting plants (0.5 - 0.6 m in height), an Allasia R1 planter was used (Fig. 1) [39]. The cultural operations for the SRC cultivation and nursery only involved weed control necessary for a high production of biomass [40-41]. In contrast to poplar plantations, in black locust plantations, fertilisation for each year of cultivation was not considered [42]. A heavy cultivator was used for stump removal (at the end of the cycle) (Tables 1-2).

For biomass harvesting, a tractor of 190 kW Case Magnum 260 EP equipped with a chipper prototype Gandini Bio-harvester was used (Fig. 2). The Bio-harvester Gandini was chosen for this experiment because it is the only machine that is capable of cutting and chipping trees simultaneously and has a large diameter (up to 300 mm). The working capacity of the Gandini Bio-harvester is about 60 Mg h^{-1} (about 100 plants h^{-1}) [43]. This value is high when compared with other machines used in vSRC harvesting [44] because the prototype is used in a small experimental area [44]. Two tractors with trailers were used for biomass transportation to the farm (a distance of about 400 metres). The manpower requirement was determined considering the number of operators and the working time to carry out every cultural operation.

Energy consumption was determined considering both direct costs (fuel and lubricant consumption) and primary energy (machine, equipment and mineral fertiliser energy contents) (Table 3) [45]. The energy output of the black locust plantation was calculated as a function of the biomass production and the primary energy biomass content (Table 3). Machine fuel consumption was determined by refilling the machine tank at the end of each working phase. The tank was refilled using a two litre glass pipe with 0.02 litre graduations, corresponding to the accuracy of the measurements. The lubricant consumption was determined as a function of the fuel consumption using a specific algorithm developed by Piccarolo [46].

The human work was expressed in manpower hour requirements for each field activity, but it was not considered from an energy point of view.

The economic evaluation was determined for every cultural operation considering both the machine costs and production factors costs (fertilisers, fuel) (Table 4). The hourly cost rate for each machine was calculated using the method proposed by Miyata [47], with prices updated to 2014. The average cost of the Gandini Bio-harvester was determined considering contractor costs. Labour cost was set at €18.5 per hour. Fuel cost was assumed to be €0.9 per kg (subsidised fuel for agricultural use). An annual utilisation of at least 500 hours (with the tractor also being used for other operations) was assumed for tractors; the power requirement was calculated by taking into consideration the data recorded during experimentation and the drawbar pull and power requirement in the different operating conditions. In addition, the tractor hourly cost was determined by the methodology proposed by Miyata [47].

In order to evaluate economic sustainability, the Net Present Value (NPV) was determined which indicates the difference between total income and total cost considering a biomass value of €100 Mg^{-1}DM. This calculation was undertaken for different land rent costs [48].

3. Results

Nearly 17 hours per year of manpower were required for a hectare of black locust SRC cultivation. The biomass harvesting required more than 58% of the total time, while the chemical weed control applications required 0.6% (Fig. 3).

Energy consumption for the cultivation and management of 100 ha of black locust SRC was 9.3 GJ ha^{-1} per year and represents about 5% of the biomass energy production (about 190 GJ ha^{-1} per year). The output/input ratio was close to 20. The largest part of energy input (33%) was linked to soil fertilisation. Harvesting and biomass transportation represented about 27% of the total energy requirements (Fig. 4).

Thus, for arable land between 50 and 200 ha, the total energy cost was found to be between 4.8% and 5.1% of the energy produced. Overall, the direct energy costs were 1.8%, while indirect energy costs were 2.9% for a 50 ha SRC cultivation, and 3.1% for a 200 ha SRC cultivation.

The production costs of SRC with a six-year cycle were closely associated with both the cultivated surface and the level of production. Considering a biomass production of 60 Mg DM ha^{-1} per cycle, equivalent to about 120 Mg WB ha^{-1}, the production cost was close to €103 Mg^{-1} DM for SRC surfaces of 100 ha (Fig. 5), a value higher than the actual Italian market price of wood chips (€100 Mg^{-1} DM).

The cultural operations that had the greatest impact on total production costs were the biomass harvesting and transportation to the farm (nearly 23.6%) (Fig. 6). Planting showed an impact on the cost greater than post-emergence treatment (weed control) and soil fertilisation, but these operations were necessary for high biomass production. In addition, land rent cost also had a high impact on the total cost. For example, considering a 100 ha SRC surface with 10 Mg DM ha^{-1} per year of biomass production and a land use cost of €200 ha^{-1} per year, the biomass production cost was €103 Mg^{-1} DM. In the case of land use cost of €400 ha^{-1} per year, the biomass production cost was €123 Mg^{-1}DM. In these cases, the land rent cost had an impact on total production costs of 19 and 30% respectively (Fig. 7). The biomass transportation cost represented 3% and 18% of the total cost for distances of 5km and 50 km respectively (Fig. 8).

4. Discussion

In general, biomass production from a black locust plantation is lower (10 Mg ha^{-1}DM per year) than for poplar plantations (12-18 Mg ha^{-1}DM per year) [36, 38, 49]. These results were obtained by using the most appropriate type of black locust for the soil characteristics of the land used for planting.

The black locust SRC plantation, in the conditions outlined (six year rotation with harvesting carried out at the end of the cycle), is very interesting in terms of energy. In fact, the output/input ratio results are higher than 20. This value is two points higher than that calculated for a poplar SRC by Manzone et al. [42]. The better results are to be attributed to the minor energy consumption for SRC management because a black locust plantation does not require top dressing, irrigation and disease control. The largest part of energy input (33%) is linked to soil fertilisation carried out at the beginning of a cycle where it is necessary to have high biomass production (10 Mg DM ha^{-1} per year) [50]. In contrast, the lowest input is linked to chemical weed control activity (0.7%). On balance, the energy input per unit of biomass produced was 5% of the energy output. This value is similar to that found in another analysis in Italy on poplar SRC [25, 42] and in Sweden on willow SRC [51].

Another advantage of black locust cultivation, in comparison with poplar plantations, concerns the manpower requirement. In fact, the value obtained in this study (17 hours per year) is about 40% lower than that calculated for a poplar SRC with the same characteristics [42].

However, the SRC economic evaluation is negative because the market price of the woodchips is lower when compared with biomass production costs. In fact, for SRC economic sustainability, the biomass price should be at least €115 Mg^{-1}DM (€15 more than the current market price). Similar results were obtained in other work undertaken in North West Italy [52].

It needs to be pointed out that this evaluation was not performed in ideal working conditions. In fact, these results were obtained considering a low biomass market value [53] and only one planting rotation. This has a significant impact on cost because ploughing, planting and stump removal represent 25% of the total cost (Fig. 6).

Nevertheless, using this cultivation model, six year-old trees with a diameter at chest height of 150-200 mm were grown. The base of the trunk, up to two to four metres in width, can be used to produce firewood with a value for energy use higher than for woodchips (up to 200 $Mg^{-1}DM$). In this case, the economic balance becomes positive although the harvesting methods for firewood are more expensive (in this case, only a chainsaw can be used). Furthermore, since the tree has a large diameter (> 100 mm), these plantations produce woodchips of high quality with a high fibre content (85–90%) and favourable particle-size distribution; this contrasts with vSRC where the biofuel produced shows a high bark content (> 20%) and mediocre particle-size distribution, and is often too rich in fines (> 10%) [34]. This consideration is very important; material with a low bark content has a high market price because it has a high heating value and a low ash content [54-56].

In addition, black locust SRC, as a result of its low energy input, produces better results compared with poplar cultivation in ethanol production, mainly in terms of environmental aspects [57]. However, black locust is a spontaneous species and shows a tendency to form pioneer forests. This situation raises biodiversity conservation issues regarding the future development of these habitats [58-59].

For poplar plantations, tree planting is a difficult operation due to the reduced available time (March and April) and because the planters used have a low working rate and high manpower is required [60].

5. Conclusions

Woodchip production by black locust SRC plantations is possible only with economic support for their cultivation, or with the optimisation of agricultural labour and biomass production in order to reduce production costs.

The choice by Italian farmers to favour the SRC cultivation model over the vSRC model is to be applauded, because, from a six year-old tree, it is possible to obtain an assortment of wood (firewood) with an economic value for energy use higher than for wood chips. Furthermore, SRC cultivation can contribute to solving the problems of traditional cultivation and to improving the relations between agriculture and the environment. In addition, since the black locust tree is a tougher species than the poplar tree, it could also be cultivated in less productive land which is not normally used for other crops.

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