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Environmental, energy and economic analysis of a biomass supply chain based on a poplar short rotation coppice in Spain

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A B S T R A C T

This paper provides an environmental, energy and economic analysis of a biomass supply chain based on an experimental poplar plantation grown as a Short Rotation Coppice in Southern Spain. The investigation was based on Life Cycle Analysis (LCA) methodology, considering two harvesting technologies and including a sensitivity analysis on the effect of transportation distance. The results show that harvesting was the most significant life cycle phase both in terms of environmental damage and economic costs, primarily due to the strong energy demand of the machinery employed in these activities. Transportation had a comparatively lower environmental and economic significance than harvesting, although the effect of this operation increased rapidly with distance. Agricultural operations related to the use of fertilizers and herbicides were found to have a limited effect on the economics of the system but they had a notable impact on certain midpoint categories relating to human and environmental toxicity, eutrophication and acid emissions. Normalized LCA results point to agricultural land occupation as the most affected environmental category of the system. The bioenergy supply system was highly energy efficient with a Cumulative Energy Demand and a Net Energy Ratio determined at 29.1 MJ/GJ and 34.0, respectively. Poplar collection by chip harvesting was less energy intensive and was more benign to the environment. The results also show a linear relationship between biomass transportation distance and impact values in all midpoint LCA indicators. Biomass collection by chip harvesting was more cost-effective than bale harvesting, while transportation costs were decisive in the economic viability of the system. However, in the conditions assumed, current wood chip prices are too low to make this project economically viable in Spain. This conclusion may be different for other locations that have reduced rental costs for land, lower irrigation needs or improved biomass production yields.

1. Introduction

Industrialized countries are developing strategies to reduce their dependence on fossil fuels and to favor the sustainable utilization of renewable energy resources for the production of power, thermal energy and transportation fuels. Modern bioenergy is expected to play a key role in this transformation of the energy sector (European Commission, 2009; IDAE, 2010; IEA, 2012). At present, most of the solid biomass employed for energy purposes is generated as a by-product of the forest, agriculture and wood-processing sectors. However, residual materials alone are unlikely to be sufficient to meet the augmented demand that is foreseen in the coming years. Short Rotation Coppice (SRC) plantations are being investigated as a means to supply large amounts of high quality lignocellulosic biomass in a controlled, sustainable and cost effective manner (ENCROP, 2009; Halford et al., 2010). In particular, the production of poplar is attracting scientific and commercial interest in many areas of the world including the Mediterranean basin (Cañellas et al., 2012; Sixto et al., 2010; Testa et al., 2014), Northern Europe (Nielsen et al., 2014; Verlinden et al., 2013) and North America (Elferjani et al., 2014; Jassal et al., 2013). This species is known for its strong resistance to frost, its capacity to re-sprout from its stump and its fast growth rates when cultivated under adequate climatic and soil conditions.

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Despite its high water requirements, industrial production of poplar is particularly well established in Southern and Northern Spain, primarily for veneer production (Tolosana et al., 2011). Conventional poplar plantations are managed in rotation periods that usually span 10–15 years, with tree densities typically ranging between 350 and 700 trees/ha and stump removal at the end of each rotation (Barrio-Anta et al., 2008; Cañellas et al., 2012; Perez-Cruzado et al., 2014). Higher densities (>15,000 tress/ha) and faster rotation cycles have been reported to increase biomass yields to values in excess of 35 t_{DM}/ha·yr (Sixto et al., 2007; Testa et al., 2014). Recent publications state that poplar plantations have the potential to supply up to 1.0% of Spain's energy demand by the year 2020 (Perez-Cruzado et al., 2014).

Despite the renewable nature of this energy resource, agricultural activities necessarily incur environmental costs that need to be quantified and managed accordingly. LCA has been widely used to analyze the sustainability of bioenergy systems (Cherubini and Stromman, 2011) and of poplar SRC plantations for the production of power (Butnar et al., 2010; Gasol et al., 2009a,b; Gonzalez-Garcia et al., 2014) and ethanol (Gonzalez-Garcia et al., 2014). These publications have all been produced by the same research group and are based on the analysis of a specific SRC in Soria (Northern Spain) planted at a density of 10,000 trees/ha and cultivated in three consecutive 5 year cycles. Net greenhouse emissions were reported to range between 1.6 and 2.0 g CO_2 eq per MJ of biomass energy (Gasol et al., 2009a,b; Gonzalez-Garcia et al., 2014). This impact was attributable primarily to the use of synthetic fertilizers and also to the consumption of diesel in the transportation of the biomass to the energy plant. Net Energy Efficiencies were calculated to range between 25 and 26 kJ/MJ for heat production and 81–83 kJ/MJ for power generation.

The economics of biomass supply chains based on SRC have also been investigated in a number of recent publications. The results are highly variable due to differences in biomass yields (which depends on many parameters like soil type, climatology, water availability, species and clone, etc.), land rental costs, wood chip market prices and the availability of public subsidies (Ericsson et al., 2009; Hauk et al., 2014; Testa et al., 2014). Gasol et al. (2010) calculated the supply cost to be between 18.7 and 24.0 €/t_{DM} for poplar wood chips intended for power generation in Southern Spain. Significantly higher costs were reported by Manzone et al. (2014) (45–115 €/t_{DM}) for poplar wood chips produced in Italy. Ericsson et al. (2009) estimated the costs of biomass generation by SRC in Europe to range between 4 and 5 €/GJ, equivalent to 72–90 €/t_{DM}.

This paper provides up-to-date information about the environmental and energy performance of a biomass supply chain based on a high density poplar SRC plantation in Southern Spain. The economic viability of the system is also calculated using the same scope, which enables a quantitative evaluation of the symmetry (or antisymmetry) in the economic/environmental significance of each one of the elements in the life cycle of the system. The analysis includes an assessment of two harvesting technologies (round baling *vs*. chip harvesting) and incorporates a sensitivity analysis of the effect of transportation distance from the plantation plot to the energy plant (10–100 km). This range of distances has been regarded as economically acceptable in publications analyzing the effect of transportation on the viability of bioenergy projects (Hamelinck et al., 2005; Ranta and Rinne, 2006).

2. Methodology

2.1. Description of the poplar energy crop

Unless otherwise indicated, the technical and economic information employed in this analysis is based on a 2.0 ha plot located in the Genil Valley (Granada, Spain) (+37° 12′ 13.72″, 3° 42′ 46.30″) planted with *Populus x canadensis* clone AF2 at a density of 13,333 trees/ha. The plot was established in 2009 and it is managed as a SRC assuming four consecutive 3 year rotations followed by stump removal at the end of year 12. Experimental data was available for the first rotation and data for subsequent rotations was estimated according to information published in the literature (as described in each case). The soil is classified as clayey silt, the plot is located at an altitude of 602 m, the average rainfall (2009–2011) is 479 mm and the average temperature (2009–2011) is 15.7 °C. Additional information about the cultivation system may be found in Cañellas et al. (2012) and in Perez-Cruzado et al. (2014).

As shown in Table 1, biomass generation at the end of the first rotation period was 51.3 tDM/ha, corresponding to an annual yield of 17.1 t_{DM}/ha × yr. This value is comparable to those reported by other authors for high density poplar plantations in Europe (Butnar et al., 2010; Gasol et al., 2009a,b; Gruenewald et al., 2007). A 10% increase in biomass production was assumed in the second rotation period (compared to first rotation) and an additional 5% production increase was considered in rotations three and four (Faasch and Patenaude, 2012).

2.2. Life Cycle Analysis (LCA) methodology

The LCA analysis was performed according to standard methodology ISO 14040-14044:2006 considering the following phases: Soil preparation and conditioning; Cultivation; Harvesting and transportation; and Soil recovery. ReCiPe 2009 Europe H (Midpoint and Endpoint) v1.09 was used to calculate aggregated impacts on selected environmental categories. The Cumulative Energy Demand (CED) of the system was calculated using CED v1.08 (Hischier and Weidema, 2010; Jassal et al., 2013). The Net Energy Ratio (NER) represents the fraction between the net energy generated and consumed by the system. SimaPro v8.0 software was used to build the models and perform calculations.

2.2.1. Goal and scope

The goals of this investigation are to quantify and evaluate:

- the environmental and energy performance of the experimental biomass supply chain,
- the effect of two harvesting technologies (bale harvesting *vs* chip harvesting),
- the effect of transportation distance (from 10 to 100 km) and,
- the economic viability of the bioenergy system in its different scenarios.

The Functional Unit (FU) employed in this analysis was 1.0 GJ of net energy in the form of poplar wood chips delivered at the energy plant.

2.2.2. Technical and environmental inventory data

Table 2 provides a summary of all the processes considered in the LCA of the biomass supply chain. Full inventories are supplied

Table 1
Populus x canadensis mass and energy yields in Southern Spain.

	Rotation				12 year average
	1st[a]	2nd[b]	3rd[b]	4th[b]	
Biomass yield (t_{DM}/ha yr)	17.1	18.8	19.8	19.8	18.9
Energy productivity (GJ/ha yr)	312	343	360	360	344

[a] experimental data for 1st rotation.
[b] estimations for 2nd, 3rd and 4th rotations.

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