Forest Systems
31 (1), e002, 11 pages (2022)
eISSN: 2171-9845
https://doi.org/10.5424/fs/2022311-18485
INIA-CSIC

RESEARCH ARTICLE

OPEN ACCESS

Economic and environmental assessment of a multifunctional poplar plantation for roundwood and wood chip production in Spain

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Abstract

Aim of study: To analyze the environmental and economic performance of a multifunctional poplar plantation (MPP), which was managed to produce timber for sawn wood and chips for bioenergy.

Study area: The plantation was located in Southern Spain producing roundwood and woodchips (from tops and branches).

Materials and methods: The life cycle assessment (LCA) methodology was chosen to perform the environmental impact assessment from a cradle-to-gate perspective. Capital goods, including machinery-manufacturing processes, were included. One oven dry tonne (odt) of forest biomass was chosen as functional unit. The economic analysis was performed using present costs and common indicators: net present value (NPV) and internal rate of return (IRR).

Main results: The harvest operations are the most environmental impacting subsystem and cultivation the costliest. Chipping was the process contributing the most to the environmental burden. The use of fertilizers, within the cultivation subsystem, had a notable impact on certain midpoint categories. In terms of climate change potential, 1 odt of delivered wood chips generated 64.1 kg CO_2-eq. When considering the whole system (including the roundwood fraction), this value was 45.2 kg CO_2-eq odt^{-1}. MPP was hardly profitable with land rental and irrigation being the most expensive items. NPV, including harvesting and transport subsystems, was 1,582 € ha^{-1}, while IRR reached 6.3%.

Research highlights: Our results allow to identify the costliest operations and those with the greatest impact to improve the system. Finally, these figures can be compared with other crop alternatives such us poplar short rotation coppice (SRC).

Additional key words: *Populus* sp.; life cycle assessment; operational cost; forest harvesting; profitability; environmental impacts

Abbreviations used: CC (climate change potential); CED (cumulative energy demand); FC (fuel consumption); FU (functional unit); HT (human toxicity potential); IRR (internal rate of return); MC (moisture content); LCA (life cycle assessment); MPP (multifunctional poplar plantation); NPV (net present value); odt (oven dry tonne); SRC (short rotation coppices).

Authors' contributions: Coordinating the research project, design: RL. Data acquisition: RL, SJH, ET. Analysis and interpretation of data: RL, SJH, ET. Software technical support: BC, GSM. Environmental analysis: RL, BC, GSM. Supervising the work: BC. Drafting of the manuscript: RL, ET. Critical revision of the manuscript for important intellectual content: ET, MTF.

Citation: Laina, R; Herrero, SJ; Corona, B; Tolosana, E; de la Fuente, MT; San Miguel, G (2022). Economic and environmental assessment of a multifunctional poplar plantation for roundwood and wood chip production in Spain. Forest Systems, Volume 31, Issue 1, e002. https://doi.org/10.5424/fs/2022311-18485

Received: 03 Jun 2021. **Accepted:** 16 Feb 2022.

Funding: The authors received no specific funding for this work.

Competing interests: The authors have declared any commercial involvements that may represent a conflict of interest in connection with their article.

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Introduction

Poplar (*Populus* × *euroamericana* (Dode) Guinier I214) plantations have been established in Spain primarily for veneer production (Tolosana *et al.*, 2011). These plantations play an essential role in supplying the wood industry since the demand for poplar roundwood is estimated in almost one million m^3 per year (García, 2018). Currently, poplar plantations cover 136,103 ha in Spain and 0.85 million m^3 are harvested yearly (MAPA, 2020a). They are common in riversides and irrigated agricultural land. In the province under study, Granada, the poplar plantation surface is around 6,000 ha (Banco de Datos de la Naturaleza, 2006); the plantations are mainly private, have an average size of 2.1 ha (Arboleda, 2014) and, for veneer production, are managed with rotation periods that usually span from 10 to 15 years in Northern Spain and 8 to 10 in Southern Spain; the plantation density varies from 350 to 700 trees ha^{-1}. At the end of each rotation, stumps are removed or grinded (Pichio *et al.*, 2012).

The plantation cycle usually involves ploughing, fertilization and irrigation. The high growth rates, the short rotation periods and the veneer log stumpage price that currently reaches and even exceeds 66 € m^{-3} (FAFCYLE, 2021), make poplar plantations an attractive investment for farmers.

On the other hand, although poplar short rotation coppices (SRC) are sparsely planted in Spain, they are attracting scientific and commercial interest for biofuel production since most of the solid biomass used for this purpose in Spain comes from by-products of the wood-processing industries and residues from agriculture and forest harvesting operations. The economy of biomass supply chains based on SRC has been investigated in several recent publications (Sixto *et al.*, 2010; Cañellas *et al.*, 2012; Perez-Cruzado *et al.*, 2014, Testa *et al.*, 2014; Schweier *et al.*, 2017). The results are highly variable due to differences in biomass yields (depending on factors such as site conditions, water availability, species and clones), land rental costs, wood chips and timber market prices and availability of public subsidies (Ericsson *et al.*, 2009; Hauk *et al.*, 2014; Testa *et al.*, 2014; San Miguel *et al.*, 2015; Schweier *et al.*, 2016).

In the last 12 years, harvesting systems in Spain started to include branches, tops and sometimes stumps for bioenergy production. Multifunctional poplar plantations (MPP) integrate traditional (roundwood) and new (chips from tops and branches) forest products in the same supply system. Therefore, MPP may be a better alternative than SRC in order to meet roundwood and biomass demands. Although MPP and roundwood poplar plantation have been studied in few scientific articles (Tolosana *et al.*, 2011; Lovarelli *et al.*, 2018; Chiarabaglio *et al.*, 2020) it has received less attention so far and no reference comparing MPP with SRC was found at the time of writing. However, there are major differences in planting densities, duration of rotation cycles, yield and machinery (Barrio-Anta *et al.*, 2008; Sixto *et al.*, 2010).

Life cycle assessment (LCA) is a methodology that evaluates resource consumption and waste generation in order to estimate the potential environmental impacts associated with production systems (ISO, 2006). It has been widely used to analyze the environmental profile of bioenergy systems and wood supply chains (Cherubini & Stromman, 2011; Murphy *et al.*, 2014; De La Fuente *et al.*, 2017). Spanish poplar SRC for energy production have also been studied under a LCA perspective (Gasol *et al.*, 2009; Butnar *et al.*, 2010; González-García *et al.*, 2014; San Miguel *et al.*, 2015). To evaluate the MPP from planting to mill gate, an environmental analysis following the LCA methodology and an economic analyses assessing the annualized NPV (net present value) and IRR (internal rate of return) were performed. These assessments provided concise indicators that allowed the comparison with the SRC management system. Therefore, this studied contributed with useful information for both decision makers and the public.

The aim of this study was to analyze the environmental and economic performance of a multifunctional poplar plantation (MPP) in Southern Spain, to identify the key processes in the system (hotspots) and to compare the wood chip production from MPP and SRC under the environmental and economic perspectives.

Material and methods

The ISO 14040 (2006) and herewith the mandatory steps have been followed in the current study for the environmental assessment.

Functional units

The reference functional unit (FU) for the inventory analysis, and for both environmental and energy assessments, was 1 oven dry tonne (odt) of wood chips (top and branches) and 1 odt of whole tree. Whole tree included all above ground leafless biomass with a distribution of 82.9% of roundwood until 8 cm of diameter and 17.1% wood chips delivered to industry (Tolosana *et al.*, 2011). One odt FU can facilitate comparison between different wood supply chains and it is in agreement with other forest system LCA studies (Johson *et al.*, 2012; Murphy *et al.*, 2014; De La Fuente *et al.*, 2017; 2018). The cumulative energy demand (CED) of the system was calculated using CED v1.08 (Hischier & Weidema, 2010). SimaPro v8.0 software was used to build the models and carry out the calculations.

Description of the commercial plantation under assessment and boundaries

The MPP chosen for the analysis was located in Granada province (Southern Spain), where the average rainfall is 497 mm. The tree density was 714 trees ha^{-1} (3.5 m × 4 m) and the rotation period was 10 years. The mean annual increment was 17.6 odt (ha year)$^{-1}$ of roundwood and 3.6 odt (ha year)$^{-1}$ of wood chips from branches and tree tops (Tolosana *et al.*, 2011). All activities involved in the cultivation process were included within the system boundaries up to the transportation to the industry (Table 1). The following subsystems were analyzed in detail:

a) Soil preparation and conditioning. Both processes were performed by a 74 kW farm tractor with a plough to carry out a 30-cm deep plowing and a cultivator for further tilling.

b) Cultivation. It comprised the plantation of one year-rods in 90 cm depth pits dug by a tractor-attached

Table 1. Subsystems and processes included in the system boundaries and field operation timeline

Subsystem	Operation/Machinery [1]	Year 1	2	3	4	5	6	7	8	9	10
Soil preparation and conditioning	• Plowing (30 cm deep)/ Moldboard 0.97 t plow attached to 74 kW/8.3 t farm tractor. FC: 14.45 kg ha^{-1}	1									
	• Scarifying / 0.67 t Rotovator attached to 74 kW farm tractor FC: 12.75 kg ha^{-1}	1									
	• Marking plantation points / Crossing points. 0.3 t attachment on 59 kW/3 t farm tractor passes. FC: 3.4 kg ha^{-1}.	1									
Cultivation	• Shallow (90 cm depth) plantation/ 0.3 spiral drill attached to 59 kW/3 t farm tractor PTO. FC: 65.74 kg ha^{-1}	1									
	• Irrigation / 2750 m^3 (ha year)$^{-1}$ in 12 doses during summer vegetative period, every 15 days.	12	12	12	12	12	12	12	12	12	12
	• Surface fertilization (550 kg ha-1 15/15/15 NPK) / 0.7 t centrifugal broadcaster on 59 kW/3 t tractor. FC: 10.2 kg ha^{-1}		1	1	1	1					
	• Mechanical weeding / 1.0 t mulcher powered by 74 kW/3.8 t farm tractor, crossed passes. FC: 122.4 kg ha^{-1}		2	2	2	2					
	• Pruning / workers with pneumatic knives on lifting platforms moved by self-propelled 24 kW/2.5 t tractors with 0.5 t telescopic booms. FC: 21.25 kg ha^{-1}		1	1	1	1					
Harvesting and transport	• Felling with chainsaw. FC: 3.13 kg ha^{-1}										1
	• Delimbing and crosscutting: 20.45 t backhoe excavator (105 kW) with Keto 750 harvesting head. FC: 81.1 kg ha^{-1}										1
	• Collecting biomass 0.25 t telescopic boom loader on 70 kW/8.7 t tractor. FC: 40.72 kg ha-1 and chipping with chipper attached to a 155 kW/10.7 t tractor 132.8 kg/ha^{-1}										1
	• Roundwood transport with a 152 kW farm tractor with a log loader and a 25 m^3 trailer. 4,416 t·km^{-1}.										1
	• Chips transportation with a 35 m^3 trailer hauled on 73 kW/3.8 t tractor (91.95 t·km^{-1} for forwarding) and 184 kW semi-trailer truck 25 km for road transport 1,520 t·km^{-1}										1
Stump grinding	• Stump drilling / 0.31 t spiral drill attached to 118 kW/ 6 t farm tractor. FC: 116 kg ha^{-1}										1

[1] FC: fuel consumption.

spiral drill. A flooding irrigation system was applied in this plantation, 12 doses from March to September. No energy consumption was needed for the irrigation. The mechanical weeding was carried out by the same farm tractor with a mulcher. Pruning operations were performed manually and mechanically using a tractor-mounted telescopic boom. Fertilization was carried out by a tractor with a centrifugal spreader attached, NPK (15/15/15) granulated fertilizers were spread. Transportation of fertilizers from the production plant to the local store was assumed to be done by truck (transport distance = 250 km) and by van from the local store to the cultivation plot (transport distance = 30 km).

c) Harvesting and transport. Harvesting was carried out by a chainsaw operator that felled the trees and a 105 kW backhoe excavator with a processing head that supported the directional felling, separated the roundwood (cylindrical stems up to 8 cm top diameter) from the biomass (crooked logs, tops and branches), crosscutted, classified and piled logs. A 152 kW farm tractor with a log loader and a 25 m^3 trailer, loaded and hauled off the logs from the harvesting site to the sawmill (15 km transportation distance). A telescopic boom loader with a raking piled the tops and branches. This biomass was chipped by a chipper attached to a 155 kW tractor. Then, a tractor with a 35 m^3 trailer hauled the chips off. Finally, a 184 kW walking floor semi-trailer truck transported the chips 25 km to the power plant.

d) Stump grinding. It included stump smashing with a driller attached to a 112 W farm tractor. The production and maintenance of machinery used in the plantation and the truck used in the transportation were included within the system boundaries. The production of other inputs such as fossil fuels (diesel and gasoline), lubricants and fertilizers were also included within the system boundaries. Production of poplar cuttings, emission due to indirect land use change, changes in soil carbon stocks, emissions at the power plant and assimilation of CO_2 by trees were excluded of the system boundaries.

Environmental inventory analysis

Primary data were used for the foreground system (processes related specifically to the poplar roundwood and wood chips) whenever possible (Table 1). These data were obtained from up-to-date current practices, machinery and prices in Southern Spain (J. Calero Tejera, manager of "Maderas y Aplicaciones Calero Tejera", *pers. comm.*, 2020; A. Ramos Fernández ex-president of "Asociación Granadina de Cultivadores del Chopo" and collaborator of European research projects WACOSYS and BIOPRO, *pers. comm.*, 2020). Secondary data were obtained from Ecoinvent v3.0 database. Energy and material input values (kg·ha^{-1}), electricity use and the specific characteristics of the machinery (size, weight and capacity) were adapted from Ecoinvent v3.0 considering the data obtained from the plantation under assessment.

Diffuse emissions of phosphates and nitrates into natural waters represent 1.5% and 30% of the total P and N applied as fertilizer, respectively (Powers, 2005; Cherubini *et al.*, 2009). Diffuse emissions of N_2O, CH_4 and NH_3 into the air represent 1.33 %, 1.0 % and 0.99 % of the total N applied, respectively (IPCC, 2006). Diffuse emission of potassium was not considered due to the lack of consensus regarding the dispersion of this element.

The SRC data needed for the comparison with MPP was obtained from a previous study in the same location (San Miguel *et al.*, 2015).

Allocation procedure

The resource requirements associated with processes that yield more than one co-product must be appropriately divided between the co-products. ISO 14044 (2006) recommends the use of physical relationships or economic values if allocation cannot be avoided. In this study mass allocation was chosen to divide the loads between roundwood and wood chips. This criterion assigned 17.1% of the environmental loads to biomass (tops, branches and rejected stems) and 82.9% to roundwood (Tolosana *et al.*, 2011). Chipping and chip transportation processes were allocated exclusively to biomass. An economic criterion would have allocated lower environmental loads to biomass (12% of the loads) due to the current Spanish market prices. However, this allocation approach would have produced less comparable results with the mainstream international research.

Life cycle impact assessment

The environmental assessment was conducted according to the characterization factors reported in the ReCiPe (H) midpoint method v.10. (Goedkoop *et al.*, 2009). The potential impacts assessed were climate change potential (CC) (kg CO_2-eq.), terrestrial acidification potential (g SO_2-eq.), fresh water eutrophication potential (g P-eq.), marine eutrophication potential (g N-eq.), human toxicity potential (g 1,4-DB-eq.), photochemical oxidant formation potential) (g non methane volatile organic compounds), particulate matter formation potential (g PM10-eq.), freshwater ecotoxicity potential (FET) (g 1,4-DB-eq.), marine ecotoxicity potential (g 1,4-DB-eq.), water depletion potential (m^3) and fossil fuel depletion potential (kg oil-eq.). The cumulative energy demand (CED) of the system was calculated using CED v1.08 (Hischier & Weidema, 2010). SimaPro v8.0 software was used for the computational implementation of the environmental inventory and calculations.

Economic inventory and methodology

The economic assessment was based on the subsystems defined in Table 1. This analysis provided the monetary valuation of each subsystem and it allowed the comparison between the MPP and the SRC management system analyzed in San Miguel *et al.* (2015).

The cash flow of a company dedicated to the production and delivery of poplar roundwood and wood chips to industry (a sawmill and a power plant) was investigated. The costs per hectare were analyzed. Operational unit costs were derived from the hourly costs' calculation using standard methods (Spinelli *et al.*, 2009; Ackerman *et al.*, 2012; Savoie *et al.*, 2012). The productivity and cost of the cultivation subsystem were obtained from local industry and farmer associations, taking into account to the most common practices (Table 2) (J. Calero Tejera, manager of "Maderas y Aplicaciones Calero Tejera" *pers. comm.*, 2020; A. Ramos Fernández ex-president of Asociación Granadina de Cultivadores del Chopo and collaborator of European research projects WACOSYS and BIOPRO, *pers. comm.*, 2020). The harvesting subsystem productivities were obtained from the data collected in a time study performed in the same area (Tolosana *et al.*, 2011). Transportation costs were calculated using an online database (Gobierno Vasco, 2017), considering the actual transport distances of 15 km for roundwood and 25 km for chips. The following costs were obtained from the mentioned local company and farmer association, and the Spanish official data (MAPA, 2020b): land rental, 660 €·(ha·year)$^{-1}$; annual irrigation cost, 297 €·(ha·year)$^{-1}$; 5 m long rods

Table 2. Multifunctional poplar plantation (MPP) economic data. Costs and aggregate values per operation

Operation /Material	Year	Machine hours ha^{-1}	Cost/Income (€ ha^{-1})	Present value (€ ha^{-1})
Land rental	1-10	----	-660	-8.301
Plowing	1	2.0	-79.4	-123
Scarifying	1	1.5	-70.93	-110
Marking plantation points	1	1.0	-33.5	-52
Rods	1	----	-714	-1,108
Planting	1	11.9	-593.62	-921
Irrigation	1-10	----	-297.11	-3.737
NPK fertilization	2-5	1.6	-208.61	-1.148
Mechanical weeding	2-5	16.0	-161.76	-890
Pruning (1st)	2	10.2	-287.16	-1,782
Pruning (2nd)	3	13.6	-312.67	
Pruning (3rd)	4	17.0	-338.19	
Pruning (4th)	5	20.4	-363.71	
Harvesting:	10		-2,008.37	-2,008
Chainsaw		13.7		
Excavator with harvesting head		6.7		
Loader (piling)		8.3		
Tractor-chipper		8.3		
Tractor trailer		2.7		
Logs loading & transport	10	22.8	-1,237.27	-1,237
Chips transport	10	1.8	-469.00	-469
Stump grinding	10	10.5	-463.74	-464
Total cost				23,569
Roundwood selling	10			24,173
Chips selling	10			3,285
Net present value			€ 1.582	
Internal rate of return			6.3%	

Data obtained from J. Calero Tejera (2020), manager of "Maderas y Aplicaciones Calero Tejera" and A. Ramos Fernández (2020), ex-president of "Asociación Granadina de Cultivadores del Chopo" and collaborator of European research projects WACOSYS and BIOPRO.

for planting, 1.0 €·plant^{-1}; and 15:15:15 NPK fertilizer, 350 €·tonne^{-1}. Indirect costs associated with the coordination and supervision of subcontracted activities were assumed to account for 16% of all direct costs. The incomes from roundwood and wood chips sales were obtained from current local poplar timber and chip market prices (68.42 € fresh tonne^{-1} for roundwood at the sawmill gate and 45.0 €·fresh tonne^{-1} for chips at plant, with 40% MC (humid basis). Investment profitability was evaluated through estimation of the NPV and IRR. The IRR was estimated using the IRR function in MS Excel®, including indirect costs and incomes. Cash inflows and outflows were actualized for the end of cultivation period, assuming a 5% annual discount rate and no inflation rate (0%) for the duration of the project.

Results

Environmental analysis

The characterization of the MPP showed that the production of 1 odt of poplar whole tree, including roundwood and wood chips from tops and branches, had a better environmental profile than 1 odt of poplar wood chips (Table 3 and Fig. 1). This was mainly due to the high energy consumed in the chipping process. A detailed analysis of the environmental profile of 1 odt of wood chips showed the subsystem contributions to impact in each environmental category (Fig. 2). The harvesting subsystem was clearly the most impacting subsystem, it had contributions ranging from 53.7% to 61.8% of the total life

Table 3. Multifunctional poplar plantation (MPP) characterization results per functional unit (1 odt of wood chips and 1 odt of whole tree)

Impact category	Unit	Wood chips	Whole tree
Climate change	kg CO_2 eq	64.1	45.1
Terrestrial acidification	g SO_2 eq	416.5	294.2
Freshwater eutrophication	g P eq	10.5	7.8
Marine eutrophication	g N eq	22.2	14.9
Human toxicity	g 1,4-DB eq	14,334	10,949
Photochemical oxidant formation	g NMVOC	562.5	344.7
Particulate matter formation	g PM10 eq	173.2	118.7
Freshwater ecotoxicity	g 1,4-DB eq	370.1	263.2
Marine ecotoxicity	g 1,4-DB eq	446.3	263.2
Water depletion	m^3	260.2	206.2
Fossil depletion	kg oil eq	17.4	10.6
CED[1]	MJ/GJ	849.5	NA[2]

[1] CED: cumulative energy demand. [2] NA: not applicable

cycle impact, depending on the category. Fig. 3 deepened the analysis of the harvesting subsystem and pointed out the key process (environmental *hotspot*) that should be improved. The chipping process showed the highest environmental impacts, contributing from 64% to 81% of the harvesting impacts, depending on the category. This was due to the high amount of diesel consumed by the chipper. In addition, chipping was the lowest productive operation. The chipping process was fully allocated to the chip production, while the rest of the harvesting activities were allocated to chips and roundwood production.

The cultivation subsystem had also an important contribution to the environmental load, from 16.4% to 39.2%, depending on the impact category. Within the cultivation subsystem, fertilization was the process contributing the most to the environmental burden (between 53% and 81% of the life cycle impacts). This was mainly due to the production of ammonium nitrate and diammonium phosphate fertilizers. On contrast, soil preparation and conditioning, and stump extraction showed the lowest relative contribution to total life cycle environmental impacts.

Economic analysis

The NPV was 1,582 € ha[1] and the IRR was 6.3% (Table 2). The cultivation subsystem was the costliest one due to the high irrigation and pruning costs (Table 2). Land rental also represented an important cost; according to the farmer local association, this price ranges from 400 €

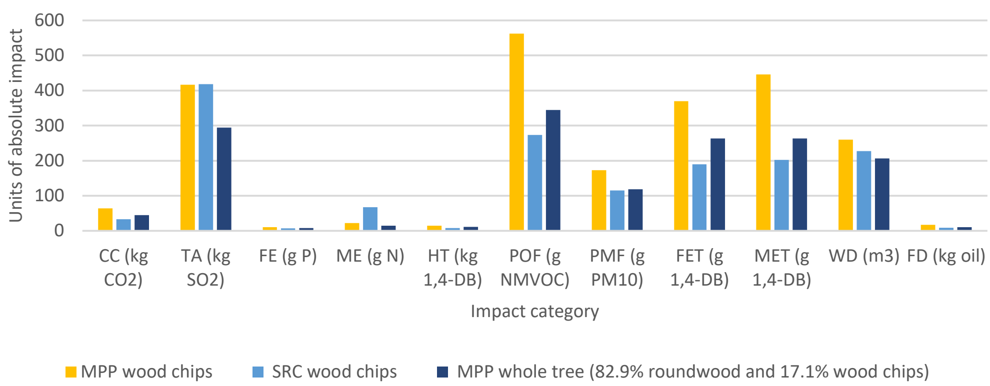

Figure 1. Comparison of chips from multifunctional poplar plantation (MPP), whole tree (roundwood and chips) from MPP and chips from short rotation coppice (SRC) characterization results per odt (oven dry tonne). CC, climate change potential; FE, fresh water eutrophication potential; ME, marine eutrophication potential; HT, human toxicity potential; POF, photochemical oxidant formation potential; PMF, particulate matter formation potential; FET, freshwater ecotoxicity potential; MET, marine ecotoxicity potential; WD, water depletion potential; FD, fossil fuel depletion potential.

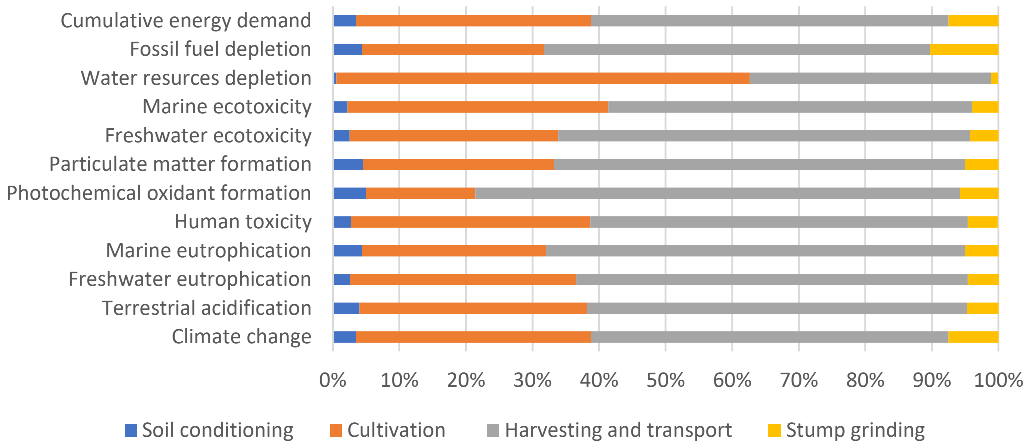

Figure 2. Contribution of the subsystems involved in the wood chip production to each impact category

to 700 €. A price of 660 €·(ha year)$^{-1}$ was chosen because it was the most updated price according to the official records of Farming Land Rental National Survey performed in 2020 (MAPA, 2020b). Years 1st to 5th of the rotation period were the costliest, because of the pruning and fertilizing operations, while years 6th to 9th only had land rental and irrigation costs. Harvesting was the third costlier operation after land rental and irrigation. Recovering branches and tops after log production was a costly operation. Piling and chipping cost 1,317 € ha^{-1} which accounted for 60% of the harvesting cost. This was equivalent to a cost of 17.1 € odt^{-1} of wood chips at the industry gate.

Discussion

Environmental analysis

SRC is being considered as an alternative crop to MPP and a detailed comparison between the environmental performance of wood chip production from MPP and wood chip production from SRC in the same location, applying the same methodology, database and system boundaries (San Miguel *et al.*, 2015) was carried out. SRC shows a similar yield per hectare, with higher density (13.333 *vs* 714 trees ha^{-1}), a harvesting is performed each 3 years *vs* 10 years of MPP; however, plantation phase is only performed each 12 years and pruning operation is not practiced in SRC. LCA analysis can aggregate these differences between both alternatives to show comparable figures. Chips from SRC showed better results in most of the impact categories than those from MPP (Fig. 1). This was mainly due to the higher biomass per hectare of biomass for chips and harvesting productivity of the SRC option. An indicator of a better machinery efficiency of SRC was fossil fuel depletion. This category in the production of 1 odt of wood chips from SRC was 52% lower than from MPP. MPP prioritizes roundwood production. The dispersion of tops and branches after log extraction caused the collection and the chipping of this biomass to

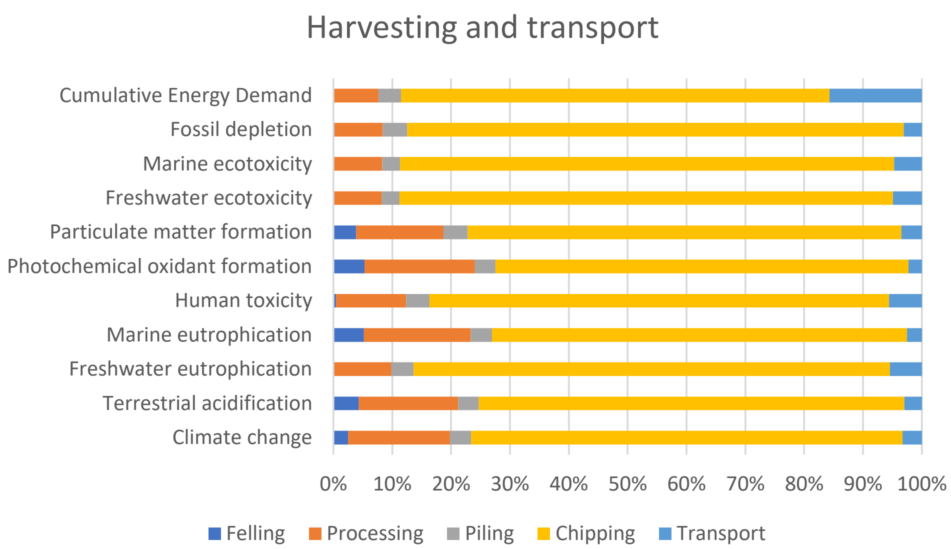

Figure 3. Contribution of the wood chip harvesting processes to each impact category

become very fuel-demanding processes. In addition, the small amount of tops and branches per hectare (17.1% of the total yield) increased the fuel consumption (FC) per odt. On contrast, SRC was 2 times higher than MPP in the Marine eutrophication category, due to the higher fertilization requirement of SRC.

If an economic allocation would have been applied, the environmental load of wood chips from MPP would have decreased in 29%. In terms of CC, one of the most commonly studied and compared category, MPP generated 64 kg CO_2-eq·odt^{-1} of wood chips, which was almost twice as high as that for SRC (San Miguel *et al.*, 2015). This result is in agreement with Schweier *et al.* (2016), who found emissions between 36 to 117.8 kg CO_2-eq odt^{-1} of wood chips from different SRC alternatives. In terms of the CED, which shows the energy required in the production process, the wood chip production from MPP required 46.7 MJ per GJ produced at the energy plant. This figure was more than double than CED of SRC (21 MJ GJ^{-1}).

In order to compare the performance of the whole system and not only the wood chip production, odt of whole tree (82.9% roundwood and 17.1% wood chips) was chosen as an alternative FU. The MPP environmental impacts were reduced between 22% and 42% when considering the whole system and not only the wood chip production. This was due to the increase of yield per hectare and the reduction of machinery FC per odt. The results calculated per total odt showed better values for MPP than from SRC in 3 out of the 12 analyzed categories, but MPP was still worse in the other 8. The greatest difference was found in the marine eutrophication category, which was 4 times lower in MPP.

Recently, Lovarelli *et al.* (2018) studied a MPP in Italy where the FU was 1 odt of roundwood and included the same system boundaries and subsystems as this study. The authors calculated the midpoint impact categories but applying ILCD midpoint method instead of the ReCiPe (H) midpoint method v.10 used in this study. The Italian MPP case study generated 59 kg CO_2-eq per roundwood odt. In order to compare to the present study, the same fraction of 84% of whole tree (odt) dedicated to roundwood was considered. The greenhouse gas emissions generated in this study were 37 kg CO_2-eq per roundwood odt. More similar figures were those related to the contribution of each subsystem. However, Lovarelli *et al.* (2018) found that the harvesting subsystem was not the most contributing subsystem to the environmental burden. This was due to the increased use of chemicals for fertilization, weed and pest control.

Economic discussion

The MPP analyzed in this study showed a NPV of 1,582 € ha^{-1}. On contrast, the poplar SRC did not show profits currently in Spain (San Miguel *et al.*, 2015). The NPV turned out to be positive only the last year, when wood and chip selling incomes were accounted for. The IRR was slightly higher than the assumed annual discount rate. The main reason to explain this fact was the low round wood price in the Granada province, since the main destination of the wood was local sawmills, instead of veneer industries. Other factor that could increase the economic balance was the machine hourly costs calculation method, which could overestimate between 20% and 40% (Hildreth & Chen, 2018) the actual operational costs in the forest practice in Spain, particularly the depreciation and maintenance machine costs.

The costs per operation and year, IRR and NPV, were compared to the obtained in the same location for an experimental poplar SRC (San Miguel *et al.*, 2015) (Table 4). The harvesting phase in SRC system was one of the factors that contributed to the non-profitability of SRC. The SRC high harvesting cost was due to more harvesting machine hours per hectare needed and more expensive hourly cost. However, other operations were less expensive in the SRC system, such as plowing and planting. MPP cost of these operations almost doubled those of the SRC

Table 4. Economic comparison between multifunctional poplar plantation (MPP) and short rotation coppice (SRC)

Operation/Cost concept	Costs / Incomes (€ ha^{-1})	
	MPP	SRC
Land rental	-660	-660
Subsoiling	-	-110
Plowing	-79	-40
Scarifying	-71	-
Marking plantation points	-33.5	-
Planting	-1,308	-650
Irrigation	-297 (x10)	-297 (×12)
NPK Fertilization	-208	-217
Mechanical weeding	-162 (x3)	-40 (×5)
Post-emergence chemical weeding	-	-42 (×2)
Pre-emergence chemical weeding	-	-51 (×4)
Pruning	-1,302 (x4)	0
Harvesting	-2,008	-1,350 (×4)
Chips transport	-469	-517 (×4)
Roundwood load & transport	-1,237	0
Stump grinding / Soil recovery	-464	-450
Roundwood selling	24,173	0
Chips selling	3,285	4,860 (×4)
Net present value (€·ha^{-1})	1,582	-2,405
Internal rate of return (%)	6.3	< 0

because of the greater depth and plant cost: 5-m plants were 20 times more expensive than 20-cm cuttings used in SRC. The cost of mechanical weeding was also higher for MPP than for SRC, because a double machine pass was needed in MPP.

Lopez *et al.* (2005) analyzed the cost of a poplar plantation for roundwood production in Spain. The calculated NPV was 730 € (year·ha)$^{-1}$, including irrigation cost. This value was higher than in the present study due to a higher stumpage price (67 € m^{-3}). Fernández *et al.* (2018) estimated an aggregated cost of 6,087 € ha^{-1} for a poplar plantation for veener production in Northern Spain, considering only silvicultural operations (irrigation and land rental were not included). This was very similar to the cost of 6,887 € estimated in this study for the same operations. However, when adding the irrigation cost, the poplar cultivation in Southern Spain became 1.6 times costlier than in Northern Spain.

Economic and environmental discussion

This section compares the differences in the results of the environmental and economic analysis. From a LCA perspective, the MPP harvesting subsystem generated most of the emissions. Chipping was a very high FC operation. This process accounted for 45% of the emissions on average. However, the harvesting subsystem represented only around 20% of the aggregated and present value of the cultivation subsystem cost. Similarly, the fertilization process had a significant contribution to the environmental impact categories (more than 30% on average) and it only represented 5% of the total cost.

On the other hand, land rental and irrigation were the costliest operations within to the cultivation subsystem, as similar studies already pointed out (Fernández *et al.*, 2018). Water depletion is an impact category directly linked to irrigation. Around 50% of the MPP water consumption was due to irrigation and the rest was due to the water requirements of other processes. Water consumption represented important economic and environmental constrains of MPP in Southern Spain when comparing it to other locations with higher rainfall. The studied plantation needed 5.4 times more irrigation than similar plantations in Southwest Germany (Schweier *et al.*, 2016) and 2.7 times more than the MPP studied by Lovarelli *et al.*, (2018) in Italy.

Conclusions

This study modeled a MPP from a life cycle assessment and economic perspectives in Southern Spain. The studied MPP was hardly profitable but showed clearly better economic results than poplar SRC for bioenergy. This difference was mainly due to the higher market price of timber compared to wood chip price for energy use. Cultivation was the costliest subsystem, because of land rental and irrigation costs. Irrigation was a major constraint in Southern Spanish poplar plantations compared to those in Northern Spain or Italy. Land rental was the second highest cost after irrigation.

The environmental impacts of wood chip production from MPP were higher than from the SRC alternative. The same trend occurred when analyzing and comparing the whole system, including the roundwood fraction. The main reason was the lower productivity and higher FC of collecting tops and branches and chipping after roundwood extraction. The harvesting subsystem generated most of the emissions, and the chipping process was identified as the system hotspot. The cultivation subsystem also greatly contributed to the environmental burden, being the fertilization process the one generating most of the emissions within the cultivation subsystem.

The outcomes of this study can be useful for the design of efficient supply chains for different industries and a more tailored subsidy framework. Although a more integrated work system that facilitates the collection and chipping of tops and branches needs to be developed.

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