



An economic overview of *Populus* spp. in Short Rotation Coppice systems under Mediterranean conditions: An assessment tool for decision-making

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ABSTRACT

Poplar Short Rotation Coppices can provide lignocellulosic raw material, promote employment in rural areas, contribute to achieving a low carbon bioeconomy and supply environmental benefits. Nevertheless, the economic feasibility of these plantations is a matter of concern and hampers the expansion of commercial initiatives. In this regard, this work aims to identify the most critical cost factors of poplar plantations under Mediterranean conditions. Data from an extensive network located at 30 different sites were used, in particular, detailed cost data for 2 rotations was available for 6 sites within the network. This study evaluates the critical factors that affect profitability, analysing the influence of the discount rate and biomass price under two productive scenarios derived from the network and evaluated as green biomass yield for the first rotation: Baseline (30.56 Mg ha⁻¹ yr⁻¹) and an Optimum (56.52 Mg ha⁻¹ yr⁻¹). Net Present Value after 12 years (4 rotations of 3 years each), ranges from -1105.54 € ha⁻¹ (Baseline) to 9620.30 € ha⁻¹ (Optimum). According to the findings of this study, profitability of poplar plantations will be achieved by ensuring optimum productivity, through an increase in current market prices (40 € Mg⁻¹) or by valuing the ecosystem services, which are not currently quantified. Sensitivity analyses were performed for the most critical cost factors: land rent (31.88 %), irrigation (16.61 %), and cut-and-chip harvesting (11.87 %), revealing that the influence of the former factor was decisive. Management diagrams that combine the discount rate, yield and biomass price are provided as tools for decision makers.

1. Introduction

In the context of the development of the bioeconomy, woody biomass as raw material for obtaining energy and/or bioproducts is considered a key resource [1,2]. The objectives as regards renewable energy sources, as an integral part of energy transition [3], are increasingly ambitious in Europe (32 % in 2030). In this context, planted forests can contribute to achieving this goal [4].

In general, the *Salicaceae* family and specifically the *Populus* genus is represented by species and hybrids of importance for wood production in many parts of the world [5] including under Mediterranean

conditions [6]. Poplar plantations growing in short rotation could represent a source of biomass and bioproducts in certain territories and scenarios, assuming sustainable management as part of the whole context at rural landscape level. In many cases, that complementarity will be key not only in terms of raw material supply but also from the perspective of achieving a just transition in the process of decarbonisation. In continental Mediterranean areas, this opportunity for increasingly depopulated regions should be explored.

The use of biomass for a range of applications such as heat for domestic thermal facilities, biomass-based electricity, biochar or second-generation biofuels, as well as the different bioproducts derived from

Abbreviations: SRC, Poplar Short Rotation Coppices; PPN, Poplar Plot Network; T, Temperature; SE, standard error (%); DBY, Dry Biomass Yield (Mg ha⁻¹ yr⁻¹); FBY, Fresh Biomass Yield (Mg ha⁻¹ yr⁻¹); M, average moisture content (%); odt, oven-dry tonnes (Mg ha⁻¹ yr⁻¹); ha, hectare; Mg, megagram; yr, year; ETP, evapotranspiration; R, rotation; v, variable; NPK, 20 N: 8P₂O₅: 10K₂O; L, land costs; C, cultural treatments; I, irrigation cost; NPV, Net Present Value (€ ha⁻¹); LEV, Land Expectation Value (€ ha⁻¹); €, euro; t, time (yr); R, revenues (€ ha⁻¹); C, cost (€ ha⁻¹); i, discount rate; Q, ratio Profit and Investment; K, investment payment (€ ha⁻¹); λ, internal rate of return; n, lifetime of the plantation (years); IRR, Internal Rate of Return; Diagram-IRR, Diagram of Internal Rate of Return; Diagram-PP, Diagram of Productivity and biomass Price.

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lignocellulosic biomass (biopolymers, additives for construction, biochemicals for biomedicine, etc.) is steadily increasing [7]. This makes it necessary to consider all aspects related to sustainability and profitability as it is vital that the two are compatible. Although the establishment of Short Rotation Coppice (SRC) is strongly influenced by economic factors [8], other issues related to sustainable management are also considered [1].

In addition, there is increasing interest in the contribution of planted forests to carbon dioxide fixation as a fast capture tool [9], this contribution varying depending on the final use of the wood. In terms of absorption, this may refer to the entire tree, when the purpose is not for energy, or limited to fractions with no energy use such as roots and leaves, considering the remaining wood as a neutral balance. In relation to roots and leaves, it has been estimated that under Mediterranean conditions the accumulation of below-ground carbon is around $1.0 \text{ Mg C ha}^{-1} \text{ yr}^{-1}$ for the first and second rotation [10] and $2.5 \text{ Mg C ha}^{-1} \text{ yr}^{-1}$ in the case of the litter [11].

Many analyses of these plantations have been undertaken from an economic perspective, although with different considerations [12,13], and some of them have also considered carbon sequestration [14]. A review carried out by Hauk et al. [8] found that 43 % of the studies revealed economic viability whereas 19 % pointed to lack of viability. The remaining 38 % showed mixed results. Recently, in certain areas of Canada, Liu et al. [15] identified a positive net return on marginal land with biomass prices of around 23.8 € Mg^{-1} , the average production cost being around 92.02 € ha^{-1} . In the western USA, the current market pricing for biomass resulted in negative financial returns from woody biomass plantations [16]. Poplar SRC has been identified as an opportunity to diversify the income of farmers in some areas of Germany with a positive annuity difference of up to 63 € ha^{-1} [17], although this is lower than that obtained from annual crops in this country [18].

In some studies, the cost of plant material was identified as the highest of those produced in the establishment phase, the cost-benefit ratio being favorable under the specific site conditions [19]. Although there are many examples of commercial cultivation in Central Europe, Schweier and Becker [18] have considered the possibility of extending the rotation or modifying the system used for the harvest to achieve the desired profitability. In southeastern USA, higher raw material prices and increased productivity have been identified as necessary for the viability of these crops [20].

Under Mediterranean conditions, a reliability assessment has been undertaken considering different scenarios for power generation [21]. The costs and benefits are closely linked to the yields obtained, which are dependent on the base materials used and the crop design (density) among many other factors. Economic evaluations are therefore very dependent on the specific scenarios on which they are based. In this regard, a comparison of irrigated poplar plantations in southern Italy, one with a short rotation period (5 years) and another with a very short rotation period (2 years) revealed a much higher gross margin under the first scenario, even better than traditional cereal farming [22]. In the south of Spain, the economic analysis carried out on a commercial plantation identified the price of land rent, harvesting and transportation as the most relevant production costs [23].

The costs derived from crop production contribute significantly to the final cost of the biomass [24,25] and there are many aspects of the agronomic process that could be optimized through applying science and innovation. Therefore, it is necessary to identify these aspects correctly as a first step to finding alternative solutions. In this type of study, the conclusions obtained often refer to very specific situations [18,26]. In fact, assumptions are frequently made in the analyses regarding important aspects such as the performance of different rotations, productivities and cultural operation costs, for which experimental data is not available although they are backed up by extensive experience [27,28].

Based on the information obtained from an extensive network of plots located throughout Spain, which cover the entire area where

poplar cultivation is viable and which are characterised by the need for irrigation due to the Mediterranean summer drought, the aims of the present work are to: i) identify the crop production costs (economic analysis) associated with poplar cultivation in SRC over the whole life cycle under Mediterranean conditions, ii) carry out a financial analysis and a sensitivity analysis that identifies the most economically relevant cost factors in two different yield scenarios, iii) analyse the influence of discount rates and biomass prices on the profitability of the investment in those same scenarios and, iv) develop a decision tool based on an extensive experimental database for poplar cultivation under Mediterranean conditions (with irrigation).

2. Material and methods

2.1. Data sources

The information used in this work comes from a Poplar Plot Network (PPN) under SRC management. The establishment of this PPN began in 2005 and some of these plots were harvested in 2018. It comprises 350 plots (sampling units within the trials), 98 trials located in 30 different locations under Mediterranean conditions and includes 48 genotypes belonging to different hybrid groups of the *Populus* genus (*P. x eur-america* (Dode) Guinier; *P. x interamericana* Brockh; *P. deltoides* March. and *P. alba* L.), (see Fig. 1). The set of sites that make up the PPN are framed in Mediterranean climate conditions characterised by a marked summer drought. The average temperature (*T*) in the vegetative period (April–September) ranged between 15.9 and 22.5 °C , the average annual *T* being 14.4 °C for the set of plots. Precipitation during the vegetative period ranged between 120 and 308 mm, with a mean value for the whole years of 543 mm. Therefore, additional irrigation was required in all sites during the summers. Around one third (32 %) were trials with an area greater than 4 ha (between 4 and 19 ha, specifically) established for both experimental and commercial purposes. A detailed description of most of this PPN can be found in Sixto et al. [29,30] and González et al. [31].

Since 2005 this network has been monitored, so dasometric and production data is available as well as, in most cases, a list of the cultural operations that have been carried out (fertilization schedule and doses, frequency of the cultural operations such as weeding, pest control and irrigation regimes in each rotation of the cycle). For the purpose of this work, different data from the PPN have been used to address all the

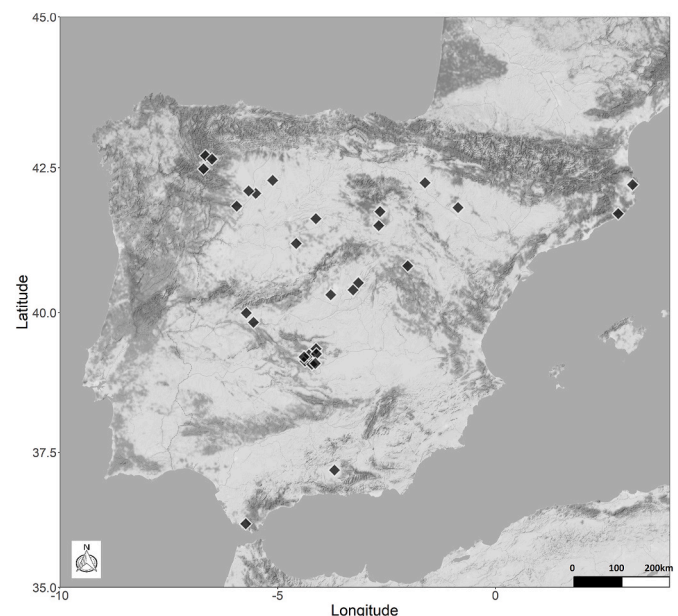


Fig. 1. Site locations of the Poplar Plot Network (PPN).

parameters used in this study, including cultural operations, management, productivity and economic data.

Detailed data from 9 trials located at 6 different sites within the network for which economic information was available, were collected and analysed to determine the costs associated with cultural operations. All trials, with an area ranging from 1.25 to 12 ha, provide real cultural operation data for at least two consecutive harvests. The trials were established with an initial density of 6666 cuttings ha^{-1} and a rotation length of 3 years. Therefore, these densities and rotation lengths (considering 4-rotation cycles), will provide the starting premises for the economic analysis carried out in this study, since most of the data on cultural operation costs within the *PPN* correspond to this design.

In order to limit the assumptions made in the study, all the information available from the *PPN* was recorded, including data for economic cultural operation costs, yield information, fertilization doses, frequency of the cultural operations such as weeding and pest control along with irrigation regimes in each rotation of the cycle.

2.1.1. Yield data

We have considered a SRC cycle of 12 years, which includes 4 rotations of 3 years. This number of rotations in a cycle of 12 years is the most predictable for a 'plantation type' under Mediterranean conditions according to the results obtained for the whole *PPN* and the rotation of maximum volume production for the majority of clones [32].

The yield value used for the 1st rotation corresponds to the average value for the plots of the *PPN* with an initial density of 6666 cuttings ha^{-1} . Taking into account that the *PPN* includes a large number of clones that are undergoing evaluation, in this "Baseline scenario" we have assumed the site productivity based on the average yield of the two most productive clones in each plot ($n = 44$ plots within 8 trials at 8 different sites), these two clones being those best adapted for the particular site conditions. Despite only using 8 out of the 30 *PPN* sites, these plots encompass a broad set of environments and genotypes growing under Mediterranean conditions.

In order to compare different scenarios and perform a sensitivity analysis, we have defined another scenario characterised by higher productivity, which we have named "Optimum scenario". This scenario was calculated using the highest yield of the most productive clone in the best 20 plots, covering densities from 4762 to 13,333 cuttings ha^{-1} ($n = 20$ plots within 12 trials at 8 different sites).

The yield value of the 2nd and 3rd rotation for both scenarios was taken from the experimental production increment found in those plots where data for 2 successive rotations were available within the *PPN*. The production of the 2nd rotation is obtained by applying a percentage of 137 % (standard error (SE) equals to 15.2 % based on $n = 34$ plots within 10 trials and 7 sites) to the 1st rotation and in the case of the 3rd rotation, a percentage of 136 % is applied to the 1st rotation (SE equals to 23.8 % based on $n = 13$ plots within 4 trials and 4 sites). Since no experimental data were available for the last rotation, the production of the 4th rotation was calculated using the trend of the average growth rate, the productivity in this case being 97 % applied to the 1st rotation. In this regard, these results are in line with those cited in the literature by other authors of similar productivity trends among rotations [33], although different values might be due to different climatic conditions, clones used and management practices. The different yields used in this work for both scenarios are shown in Table 1.

2.1.2. Cultural operation inventory

We have listed the relevant operations for optimal development of the plantation, taking as a reference the operations carried out in the *PPN*. Most of the operations performed in the *PPN* followed a common protocol described in Sixto et al. [34].

Irrigation was applied in each trial according to the evapotranspiration (ETP) of the plantation area. The irrigation doses used in this work are based on the experience gained from the *PPN* (Fig. 2).

Weed control treatments were limited to those considered essential

Table 1

Yield for 4 rotations of 3 years in two different scenarios. Cycle of the SRC: 12 years.

Rotation	Baseline scenario		Optimum scenario	
	Dry Biomass	Fresh Biomass	Dry Biomass	Fresh Biomass
	Yield (DBY) odt	Yield (FBY)	Yield (DBY) odt	Yield (FBY)
		M \approx 55 %		M \approx 55 %
	(Mg ha^{-1} yr^{-1})	(Mg ha^{-1} yr^{-1})	(Mg ha^{-1} yr^{-1})	(Mg ha^{-1} yr^{-1})
1 st	13.80	30.56	25.64	56.52
2 nd	18.91	41.87	35.13	77.43
3 rd	18.77	41.56	34.87	76.87
4 th	13.39	29.64	24.87	54.82

Yield for the 2nd, 3rd and 4th rotations obtained by applying a percentage of 137 %, 136 % and 97 % respectively to the 1st rotation yield.

M: average moisture content found in the *PPN*; odt: oven-dry tonnes.

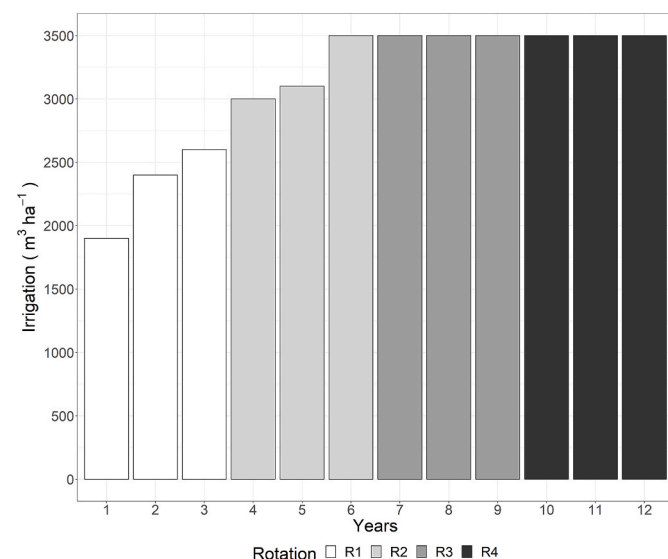


Fig. 2. Irrigation doses for SRC cycle of 12 years with 4 rotations of 3 years.

to maintain low infestation. A pre-planting treatment for perennial weeds where necessary was included as a variable (v) cultural operation (Table 2). Although this was the common protocol applied to the *PPN*, in certain situations, the absence of control or extemporaneous invasions caused a level of infestation that led to a greater need for further treatments.

Fertilization was not applied in 40 % of the *PPN* trials at the beginning of the cycle. In the remaining trials (60 %), this application was mainly carried out with a 20 N: 8P₂O₅: 10K₂O (NPK) inorganic fertilizer, between 200 and 600 kg ha^{-1} yr^{-1} . In some limited trials, calcium ammonium nitrate at 27 % was used. For the purpose of this work, NPK fertilization has been included in the list of cultural operations. We considered this cultural operation as a variable (v) operation depending on the management and consisting of one application of 300 kg ha^{-1} in the first year of each rotation.

Finally, in relation to pests and diseases, the applications were sporadic in the *PPN* and limited to pest control. There were occasional fungal diseases but these did not require treatment, partially thanks to the use of plant materials with a high degree of tolerance to the climatic conditions. In any case, it is advisable to use tolerant plant material. For these reasons, this cultural operation has been considered as a variable (v) operation, depending on the needs of each plantation or even each rotation.

The details of the cultural operations based on well-managed poplar SRC under Mediterranean conditions and the timing of applications

Table 2

Selected cultural operations structured in different categories considering land costs (L), cultural treatments (C) and irrigation cost (I).

Cost type		Cultural operation	Cycle year												
			0	1	2	3	4	5	6	7	8	9	10	11	12
SRC management	L	Insurance		x	x	x	x	x	x	x	x	x	x	x	x
	L	Soil survey	v												
	L	Land rental		x	x	x	x	x	x	x	x	x	x	x	x
Soil preparation	C	Subsoiling ^a		x											
	C	Fertilization ^b		v			v			v			v		
	C	Ploughing ^c		x											
Planting	C	Cutting stems		x											
	C	Planting ^d		x											
Weed control	C	Pre-emergence ^{se}		v			x			x			x		
	C	Post-emergence ^{se}		x			x			x			x		
	C	Mechanical ^f		x	x		x	x		x	x		x	x	
Pest control	C	Chemical ^e		v			v			v			v		
Irrigation	I	Irrigation system		x											
	I	Maintenance			x	x	x	x	x	x	x	x	x	x	x
	I	Water&Electricity		x	x	x	x	x	x	x	x	x	x	x	x
Harvest	C	Cut-and-chip ^g harvesting ^h				x			x			x			x
Stool removal	C	Chemical ^e													x

x: needed cultural operation; v: variable cultural operation, depending on the management; *: Chemical treatment. ^a Tractor (71-151 kW)+ subsoiler: 1.3 Machine hours ha⁻¹; ^b Tractor (90 kW)+ spreader: 1.2 Machine hours ha⁻¹; ^c Tractor (151kW)+ cultivator 3 rows and 25 tines: 3.5 Machine hours ha⁻¹; ^d Tractor (167 kW)+ Biopoplar 2 rows planting: 3.3 Machine hours ha⁻¹; ^e Tractor (90 kW)+ sprayers: 1.2 Machine hours ha⁻¹; ^f Tractor (90 kW)+ cultivator 9 tines chisel: 5.5 Machine hours ha⁻¹; ^g Cut and chip harvester (377 kW)+ coppice header Biopoplar: 3.5 Machine hours ha⁻¹; ^h Tractor (151kW)+ trailer: 2.4 Machine hours ha⁻¹.

throughout the entire cycle are shown in Table 2. In order to facilitate cost analysis, these costs have been separated into three cost categories: land costs (L), cultural treatments (C) and irrigation cost (I). Irrigation has been considered as an independent category from the rest of the cultural treatments, since it is a practice that is not generalized outside the Mediterranean area.

2.1.3. Chip biomass sale price

The chip biomass price assumed in this study is 40 € Mg⁻¹ at the plot entrance ($M \approx 55\%$) in accordance with the actual market and pricing obtained from the sector.

2.2. Economic feasibility

The decision to implement a poplar SRC almost always depends on its economic profitability. To carry out the economic feasibility study, i) all cultural operation costs registered in the database of the PPN were quantified, ii) two typical budgeting indicators to estimate financial viability of the project were calculated: Net Present Value (NPV) and Land Expectation Value (LEV), iii) a sensitivity analysis based on two different scenarios was carried out (Table 1) taking into account the main costs of the poplar SRC, iv) the influence of varying discount rates has been analysed, considering the effect of different biomass prices on the profitability of the investment through a graphical output in which the Internal Rate of Return (IRR) in two different scenarios can be compared (Table 1) and, v) an assessment tool for decision-making has been proposed that allows variations in productivity and chip biomass price to be contemplated in order to evaluate the profitability of poplar SRC investments under Mediterranean conditions.

2.2.1. Cultural operation cost analysis

We have calculated the average costs of each cultural operation carried out in 9 large-scale commercial plantations belonging to the PPN. The respective cultural operation considered is shown in Table 2.

All values are expressed for the same base year in euros per hectare. 2011 was taken as reference year since almost all the plantations from which we obtained the economic data were established that year. All average costs including the cost of the agricultural supplies (e.g. herbicide, fuel, fertilizer, etc.) were measured before taxes.

2.2.2. Financial analysis

2.2.2.1. Net present value. Net present values were calculated based on 2011 prices and assuming a real discount rate of 5 % over the lifetime of SRC (12 years), which includes 4 rotations of 3 years. The discount rate value of 5 % has been assumed taking into account the economic evaluation review by Hauk [8] of 37 SRC studies (the majority in Europe). This review revealed that interest rates used for economic calculation varied from 3 to 7 %, with a median rate of 5.5 %. Recently, Soliño et al. [35] in a study of landowners' attitudes towards woody energy crops, demonstrated that the discount rate implicitly used exceeds the 4 % rate commonly used in forest economics literature.

To calculate all the outflows, we use average costs for each cultural operation carried out in 9 large-scale commercial plantations belonging to the PPN, and the cultural operations needed in a well-managed poplar SRC under Mediterranean conditions (Table 2). The revenues were calculated based on a chip biomass price of 40 € Mg⁻¹ ($M \approx 55\%$) and the biomass production shown in Table 1, according to Eq. (1).

$$NPV = \sum_{t=1}^n (R_t - C_t) e^{-i(t-1)} \quad \text{Eq.1}$$

where NPV is the Net Present Value (€ ha⁻¹), t is time (years), n is lifetime of the plantation (years), i is the discount rate and cash flow is the revenues (R) minus costs (C) for each year (€ ha⁻¹).

Net Present Value is an indicator of absolute profitability associated with an investment. Another important indicator for relative profitability is the ratio between Profit and Investment [36], according to Eq. (2).

$$Q = \frac{NPV}{K} \quad \text{Eq.2}$$

where Q is the ratio between Profit and Investment, NPV is the Net Present Value (€ ha⁻¹) and K is the investment payment.

2.2.2.2. Land Expectation Value. The estimation of the theoretical land value is known as the Land Expectation Value (LEV). The LEV represents the value of all future costs and revenues assuming that the rotation will be replicated an infinite number of times in the future [36], according to Eq. (3).

$$LEV = \frac{NPV}{e^{it} - 1} \quad \text{Eq.3}$$

where LEV is the Land Expectation Value (€ ha^{-1}), NPV is the Net Present Value (€ ha^{-1}), t is time (years) and i is the discount rate.

2.2.3. Sensitivity analysis

The most important cultural operation costs have been identified and three independent sensitivity analyses were carried out using the following variables:

- (i) Land rental costs, considering a range from 0 to 600 € ha^{-1}
- (ii) Water and electricity costs within irrigation cost. This factor has been considered in order to quantify the impact of this practice, considering a range of irrigation dose reduction of up to 25 % and a range of irrigation dose increment of up to 15 %
- (iii) Cut-and-chip harvesting costs, considering higher and lower costs for this practice compared with our database prices with a range from 2 to 6.5 € Mg^{-1}

These three variables were analysed in two different yield scenarios described in Table 1. Valuations were carried out using the “ggplot2” package implemented in R 3.6.3 [37].

2.2.4. Analysis of different discount rates and biomass prices linked to an evaluation of the Internal Rate of Return

Different discount rates ranging from 0 % to 15 % and biomass prices with a range from 30 to 100 € Mg^{-1} ($M \approx 55$ %) were tested in order to analyse the influence of this parameter on NPV under the two scenarios proposed (Table 1).

The diagrams have been built with NPV on the y-axis, the discount rate on the x-axis and the different biomass prices plotted on the isolines solving Eq. (1).

Graphical representations of the interaction of these three parameters: discount rates, biomass prices and the NPV values were created using the “lattice” package implement in programme R [38]. The xyplot function was used to produce a two-dimensional graphic in which the NPV obtained after 12 years is related to the value of the discount rate and the sale price of the chip biomass. The rate that is produced when reference lines cut the x-axis for a NPV value equal to zero will be the IRR of the investment.

An investment is viable if the internal rate of return λ (Eq. (4)) is higher than the discount rate (i), according to Eq. (4).

$$NPV = 0 = \sum_{t=1}^n (R_t - C_t) e^{-\lambda(t-1)} \quad \text{Eq. 4}$$

where NPV is the Net Present Value (€ ha^{-1}), t is time (years), n is lifetime of the plantation (years), cash flow is the revenues (R) minus costs (C) of each year (€ ha^{-1}) and λ is the Internal Rate of Return (IRR).

IRR is easily identified in the graphical output provided in this study and is represented for all possible biomass prices and discount rates evaluated under the two different scenarios (Table 1).

2.2.5. Simple assessment tool for decision-making

An assessment tool based on real-cost data was developed, focusing on the interaction between productivity and chip biomass price using a simple diagram. It allows these factors to be varied from the perspective of decision-makers in order to obtain information on the profitability of investments based on Eq. (1).

This tool was built by putting the average productivity ($M \approx 55$ %) of the first rotation (3 years) on the y-axis, the chip biomass price on the x-axis and plotting the resulting NPV values obtained after 12 years on the isolines solving Eq. (1).

Graphical representations of the interaction of these parameters were created using the “lattice” package of the statistical programme R

[38].

3. Results and discussion

3.1. Cultural operation cost analysis

The respective cultural activity average costs per hectare and per tonne are shown in Table 3. The frequency represents the number of annuities in which this cost has occurred throughout the entire growth cycle of 12 years.

The two highest costs in the 1st year, as regards the establishment of the SRC, were attributable to the implementation of the irrigation system 1683.34 € ha^{-1} and the cost of the cuttings 1030.77 € ha^{-1} (Table 3). The combination of these two factors account for 2714.11 € ha^{-1} representing 16.03 % of the total. The establishment costs, including cuttings and planting together with the soil survey, subsoiling and irrigation system, are of considerable importance for the farmers given that the revenues are deferred over time. Unlike agricultural crops, SRC are characterised by high initial costs and long-term irregular revenues [28].

Among the costs of the SRC corresponding to each year, the highest was land rental cost. We have assumed a land rental cost of 473.18 € ha^{-1} , which is the average rental price in the PPN. This cost is lower than the average price of irrigated agricultural land lease in Spain (565 € ha^{-1}), which varies depending on location, starting at 350 € ha^{-1} up to 780 € ha^{-1} [39]. Studies conducted under Mediterranean conditions have identified land rental as the most critical factor [21], while others have reported that it can have an important effect on financial profitability [40]. Elsewhere in Europe, other authors have also identified this factor as having a major impact on the profitability of the plantation when considering a land rental of 250 € ha^{-1} [27].

According to our study, irrigation costs, which comprise the irrigation system, maintenance and the annual costs of water and electricity over the whole cycle (12 years) total 5021.96 € ha^{-1} . Irrigation is an indispensable operation not only for the survival of the plants under Mediterranean conditions but also to achieve the productivities considered in this study [41], which are clearly higher than those attained in other non-irrigated areas of Europe [27]. In this study, a drip irrigation system was used for more efficient water use, despite the initial investment costs being high [18].

Details of the main costs grouped into the three different categories are analysed in Fig. 3 in order to identify the cost factor which most affects the profitability of the SRC. In this regard, the main cost factor is land rental which accounts for 31.88 % of the total. The second most relevant cost factor is the water and electricity associated with irrigation, which account for 16.61 %. Finally, cut-and-chip harvesting represents 11.87 %. These three-unit cost factors represent 60.36 % of the total cost of the project.

Evaluated at present values, the three different cost categories (cultural, land and irrigation cost) account for 37.22 %, 32.27 % and 30.51 %, respectively, of the total costs. Total irrigation costs identified in this study have a greater impact than those reported by other authors under similar conditions [42], which made up 11.7 % of the total SRC economic cost. This is mainly due to the difference in irrigation system used and the lack of implementation at the beginning of the plantation. Land costs are strongly dependent on the location of the SRC, which makes comparisons difficult. The percentage corresponding to cultural operation costs of 37.22 % is lower than that observed in other studies [42].

In line with the results found in this study for the remaining cultural operation costs, which have a minimal impact on the profitability, other authors have found that maintenance costs, fertilization, pest control, and weed control, account for only a small share of the overall costs [8].

3.2. Financial analysis

Fig. 4 shows the present values of the yearly cash flows of the poplar

Table 3
Average cost per hectare and per tonne of the selected cultural operations separated into different categories according to land costs (L), cultural treatment costs (C), and irrigation cost (I).

Cost type		Cultural operation	Mean Costs (£ ha ⁻¹)	Baseline Scenario		Optimum Scenario		Frequency of activities per cycle
				Mean Costs (£ Mg ⁻¹)		Mean Costs (£ Mg ⁻¹)		
SRC management	L	Insurance	5.77	0.16	0.09	0.09	12	
	L	Soil survey	92.59	0.21	0.12	0.12	1	
	L	Land rental	473.18	13.18	7.12	7.12	12	
Soil preparation	C	Subsoiling	97.32	0.23	0.12	0.12	1	
	C	Fertilization ^a	156.47	1.45	0.79	0.79	4	
	C	Ploughing	63.62	0.15	0.08	0.08	1	
	C	Cuttings ^b	1030.77	2.39	1.29	1.29	1	
Planting	C	Planting	339.26	0.79	0.43	0.43	1	
	C	Post-emergence ^c	71.68	0.67	0.36	0.36	4	
Weed control	C	Mechanical	75.08	1.39	0.75	0.75	8	
	C	Pre-emergence ^c	67.43	0.16	0.08	0.08	1	
	C	Chemical	165.73	1.54	0.83	0.83	4 ^d	
Pest control	I	Irrigation system	1683.34	3.91	2.11	2.11	1	
	I	Maintenance	27.39	0.70	0.38	0.38	11	
	I	Water&Electricity	253.11	7.05	3.81	3.81	12	
Harvest	C	Cut-and-chip harvesting	556.37	5.16	2.79	2.79	4	
Stool removal	C	Chemical	67.43	0.16	0.08	0.08	1	

^a 300 kg ha⁻¹ NPK 20:8:10.^b 6666 cuttings ha⁻¹.^c Chemical.^d Considering a repeated treatment after 2 weeks.

SRC, including the three cost categories and the revenues for the Baseline scenario (Table 1). Under this average productive scenario and considering all cultural operations included in a well-managed SRC under Mediterranean conditions (Table 2), the NPV was −1105.54 € ha⁻¹ over the lifetime of 12 years, and the LEV was −2450.28 € ha⁻¹.

In the Optimum scenario (higher productivity) the NPV is positive, reaching a value of 9620.30 € ha⁻¹, with a LEV of 21,233.13 € ha⁻¹. This shows the importance of achieving an optimum level of productivity to compensate the investments made in the plantation. The profit:investment ratio under the Baseline scenario is 0.92, meaning that for each euro invested, the plantation has generated a discounted profit of 0.92 €. This indicator of relative profitability reveals that the investment would not be attractive for investors. However, under conditions of higher productivity (Optimum scenario) this ratio is 1.70, which could change the perspective of the investor.

NPV values reported in other studies within Europe were positive in some cases and negative in others, ranging from 250 to −485 € ha⁻¹ [12, 21,27]. Results reported by Faasch and Patenaude [28] in Germany revealed higher SRC profitability, reaching a total of 3830 € ha⁻¹. However, the differences in biomass price and in the lifetime of the plantation along with the fact that irrigation is necessary in our case makes it difficult to compare NPV values.

Along with ensuring an optimum level of productivity, another key factor for plantation profitability is the biomass price. In this study, the only input considered was the chip biomass produced to obtain energy. Quantifying extra inputs such as ecosystem services should lead to improved returns. One of the main ecosystem services of these plantations is the reduction of greenhouse gases and carbon sequestration [43–45]. However, it is also important to consider that SRC reduce soil erosion, groundwater nitrate content and surface runoff [46]. They also provide diversity in the agricultural landscape and are a reservoir of different fauna (birds, arthropods, etc.) [47]. Additionally, SRC can be used in phytoremediation [48]. It is therefore necessary to develop valuation systems for ecosystem services and quantify them with a market price. These new inputs would make poplar SRC investments viable under conditions of average productivity. Moreover, given the current dynamic development of the bioproduct markets [49], the combination of biomass as a raw material for obtaining bioenergy along with the supply of bioproducts could improve the economic and resource-use efficiency of biomass and provide additional revenues.

The profitability of poplar SRC depends heavily on plant density and coppice rotation. Some authors have found that poplar plantations with higher densities than that used in this study are more productive [50], although when it comes to minimising costs, other authors have chosen lower densities, thus assuming lower productivities [22] and longer rotations (5–7 years), but better chip qualities and therefore higher market prices [51]. However, longer rotations produce trees with larger diameters, which makes harvesting more difficult. Furthermore, Timber Investment Management Organizations normally reduce the rotation age to achieve a quicker return on the high establishment costs [52]. In line with the rotation length chosen in this study, other authors concluded that with 3-year harvest rotations, poplar SRC can contribute to agronomic and environmental sustainability thanks to its high yield and energy efficiency (output/input) [53].

3.3. Sensitivity analyses

Fig. 5 shows how the variation of the three most influential cost factors: land rental costs, the inputs linked to irrigation and the harvesting system under two scenarios based on their productivity (Table 1) affect the economic results.

3.3.1. Land rental costs

The economic results are very sensitive to land rental costs. In the Baseline scenario (Fig. 5, left side) for the real average rental price, NPV is −1105.54 € ha⁻¹. In the Optimum scenario, associated with a more

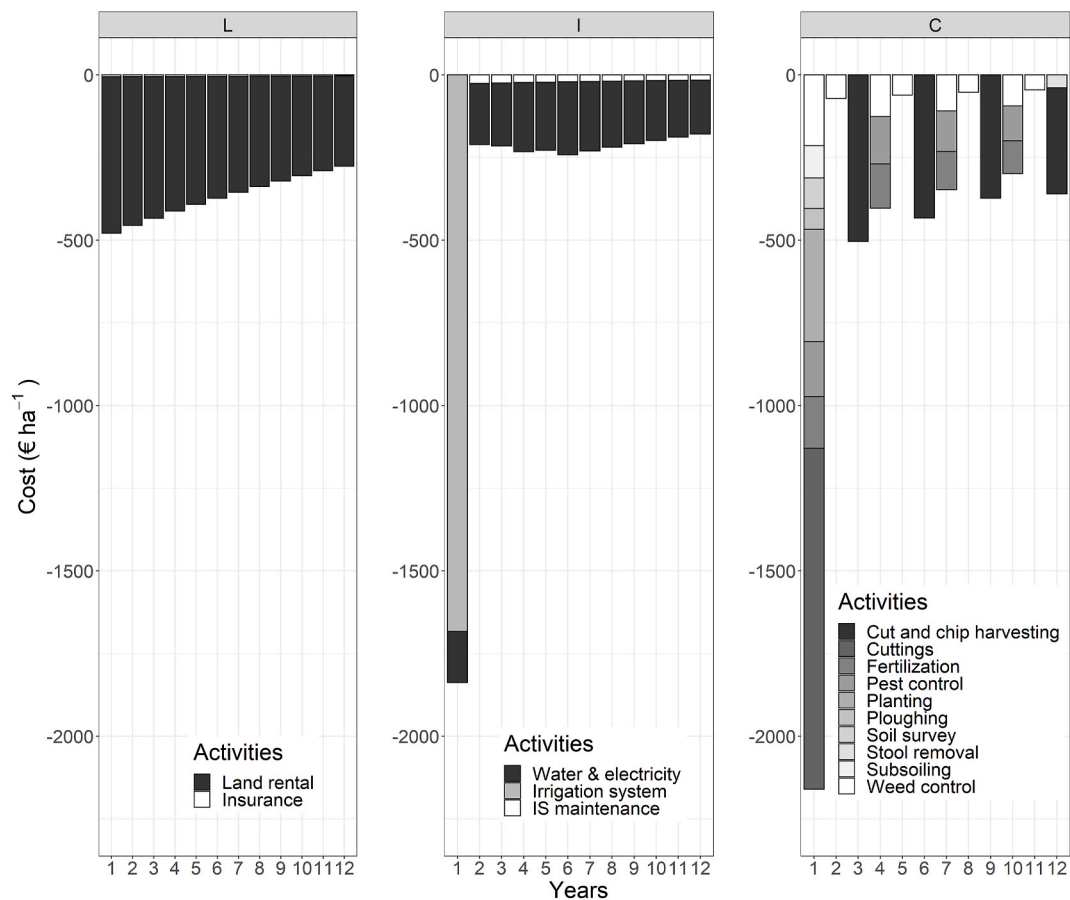


Fig. 3. Yearly Cash out-flows per operation. I: Irrigation costs, C: Cultural costs, L: Land costs, IS: Irrigation system.

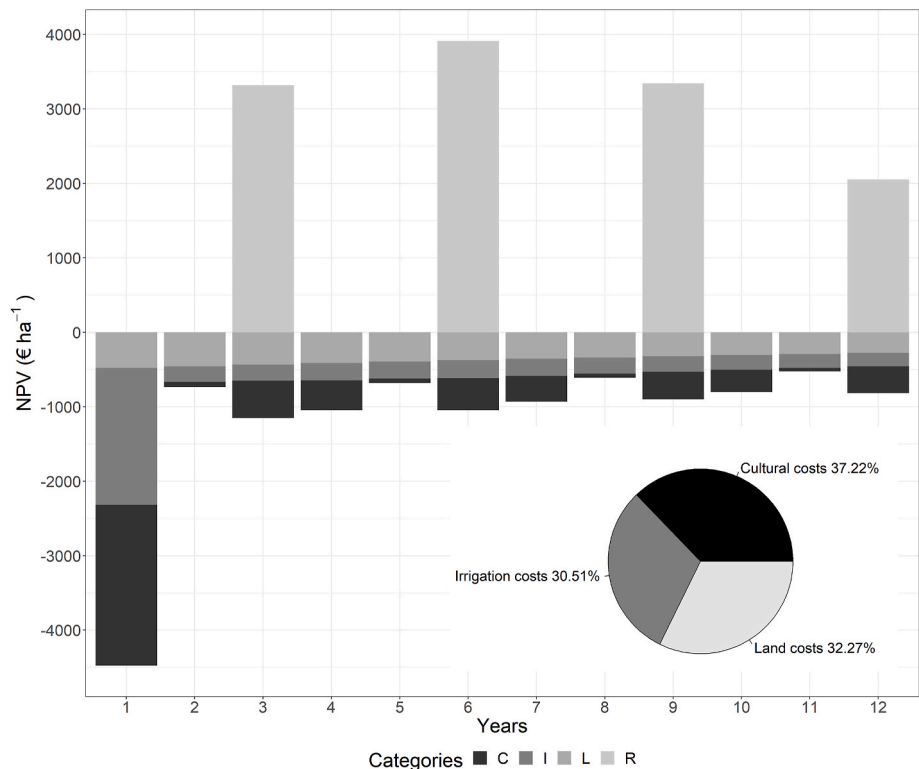


Fig. 4. Cash in-out-flows per year according to Baseline scenario. I: Irrigation costs, C: Cultural costs, L: Land costs, R: Revenues (Chip biomass).

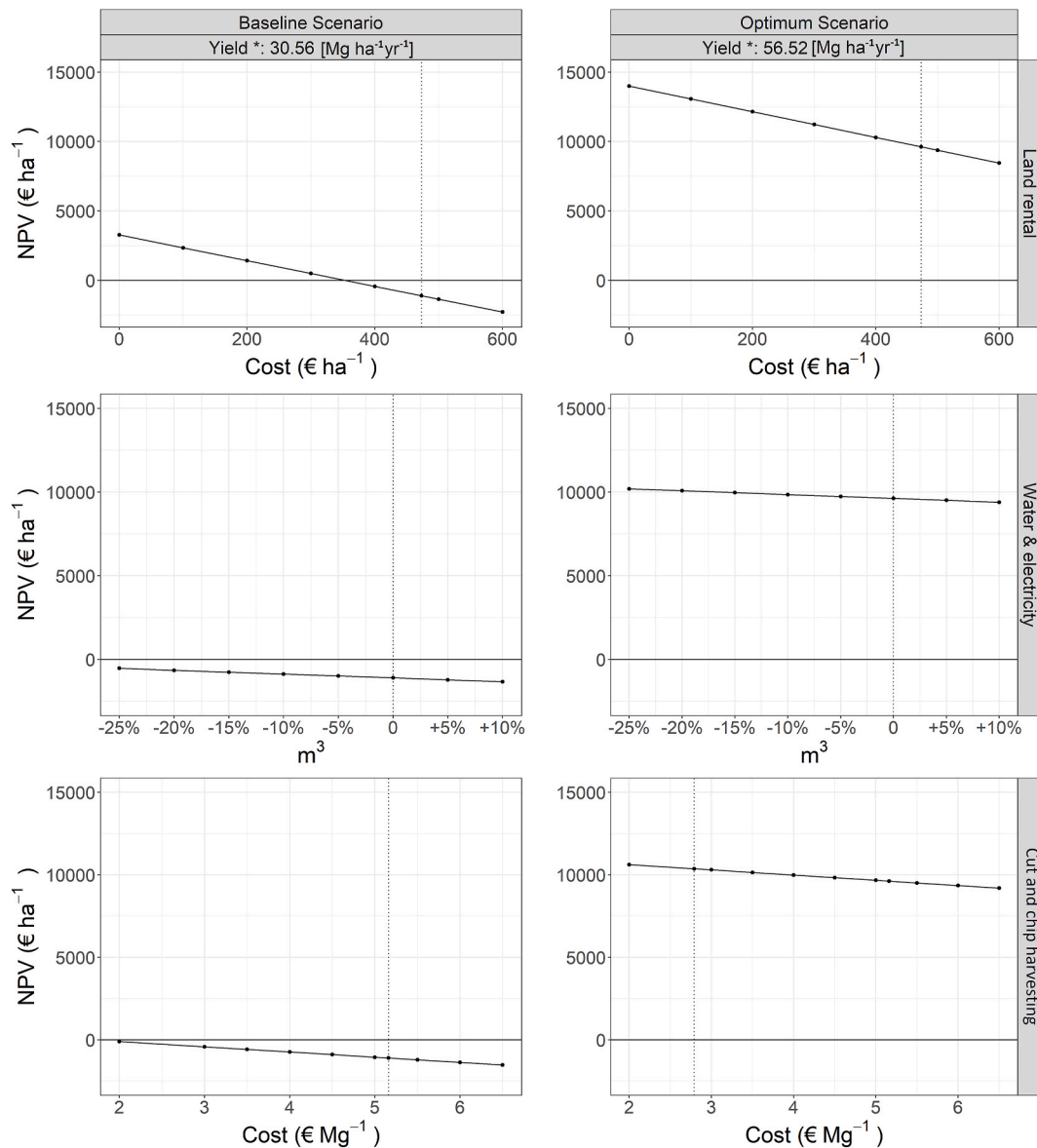


Fig. 5. Results of the sensitivity analyses showing the impact of the three highest costs identified under two different yield scenarios. *: Yield with a $M \approx 55$ %; cycle: 12-year SRC (4 rotations of 3 years); dotted line in the graphs shows average cost values used in this study (Table 3).

productive situation (Fig. 5, right side), the NPV reaches 9620.30 € ha⁻¹. To obtain a positive NPV in the Baseline scenario, land rental costs have to be lower than 353.67 € ha⁻¹. A totally different situation is that of the Optimum scenario, which achieves positive NPV values over the entire price range.

There is a reasonable possibility that farmers own the land and in such cases this becomes a negligible cost. Where that is the case, even in the least productive scenario (Baseline scenario), a positive NPV of 3271.94 € ha⁻¹ would be achieved. In the Optimum scenario the NPV would reach a value of 13,997.80 € ha⁻¹.

Other possibilities such as farmers' associations or consortia with companies could also be considered as a means to minimise this cost. Additionally, some authors have highlighted non-agricultural values such as the environmental values (landscape, biodiversity, leisure, cultural inheritance, a guarantee of food supply, food safety, and rural culture), which enable the creation of new utilities associated with the land factor [54,55]. These environmental values are part of the ecosystem services of these poplar SRC linked to the land factor, the specific cost of which will be reduced where these services have a market price.

3.3.2. Drip irrigation costs (water and electricity)

In Fig. 5, we analyse the impact on the NPV of a -25 % to +10 % change in water consumption with no effect on biomass productivity through improving water use efficiency. The NPV displays scarce sensitivity to these changes, the Baseline scenario values remaining negative over the whole range of irrigation considered while values remain positive under the Optimum scenario.

Irrigation requirements are highly dependent on site characteristics, such as soil and climatic conditions, as well as on the age and density of the plantation [31], ranging from 800 to 4000 m³ ha⁻¹ yr⁻¹ [30]. Under Mediterranean conditions, it has been shown that irrigation can be reduced by around 20 % without significant loss in biomass production for the most productive genotypes [31]. Considering this premise, under the Optimum scenario, the resulting NPV is equal to 10,076.48 € ha⁻¹ when the irrigation dose is reduced by 20 %.

In parts of Europe where irrigation is not applied, precipitation always has a positive effect on the growth of poplar SRC [56], regardless of the genotype, the most important period in terms of precipitation being from May to July [57]. Other authors have also highlighted the dependency on irrigation in Mediterranean areas in order to reach these

high productivities per hectare and have pointed to the environmental disadvantage associated with this high water consumption [21,58]. Water is a limited resource in Spain and other Mediterranean areas, hence the use of irrigation is an aspect of major concern given the overuse of this scarce natural resource [1].

The transition towards a bioeconomy-based model involves challenges such as the sustainability of biomass raw material. In this context, other methods of irrigation should be considered, for example using recycled waste water, combined with the selection of suitable genetic material. Another avenue of interest is to identify genotypes with greater hydric stress tolerance allowing irrigation doses to be reduced without affecting productivity.

In this context, progress has been made in different areas such as the search for drought tolerant genetic material [59], the study of water use efficiency [31,60] or the reuse of water from different sources [61], although there is still a lot of work to be done if irrigation doses are to be reduced without affecting productivity.

The possibility of irrigating SRC using recycled wastewater could constitute a new approach for sustainable biomass production and potential economic savings. In fact, this possibility has been explored in the USA, where recycled wastewater is used for the production of poplar biomass for a biorefinery [62]. Similarly, research conducted in Sweden points to the environmental advantages as well as economic benefits to farmers of using sewage sludge and wastewater in SRC [63]. More specifically, under Mediterranean conditions, a vegetation filter for pollutant removal using poplar SRC was evaluated over a 3 year period. This vegetation filter was irrigated using recycled wastewater and displayed efficient removal of wastewater-originated pollutants [64].

This challenging new irrigation scenario provides the possibility of combining biomass production with water reuse, thus modifying the economy of the plantation. In this regard, progress is being made in the selection of materials for Mediterranean conditions that can be irrigated with reused water [65]. Furthermore, the use of solar energy for the electrical requirements of the irrigation system combined with the use of waste water would further improve the profitability and sustainability of the poplar SRC.

3.3.3. Cut-and-chip harvesting costs

Sensitivity of the NPV to the variation in cut and chip harvesting costs per unit biomass was low. For the Baseline scenario, it was not possible to achieve a positive NPV only by reducing this cost. However, in Optimum scenario we achieved improved returns for the 12- year cycle, with values of up to 9000 € ha⁻¹ over the entire range of costs for cut-and-chip harvesting.

Many studies have shown that the cut-and-chip harvesting cost has an important impact on the economic feasibility of poplar plantations [26,66], highlighting the fact that modern technology allows a notable reduction in harvesting cost [67]. Over the PPN as a whole, the most efficient harvesting system was the cut-and-chip system, which converts the standing biomass into chip biomass in a one-step operation. The average cut-and-chip harvesting costs found in the PPN were 5.16 € Mg⁻¹ (M ≈ 55 %). This harvesting system is recommended for SRC given the high performance, productivity and profitability associated with this system [26]. The cutting head is a specialised 'coppice header' attached to a harvester. Other options should be explored to further reduce the cost of harvesting.

A review of harvesting costs carried out by Vanbeveren et al. [68] concluded that this cost can vary considerably, from 6 to 99 € Mg⁻¹ (M ≈ 55 %). If these costs are compared with the average cut-and-chip harvesting costs (9 € Mg⁻¹) calculated using models developed by other authors [69,70], we find that our cost is lower, mainly due to higher productivities achieved in the PPN.

In order to minimise these costs, the shared use of agricultural equipment among several farmers, such as large machines operated by contractors, would contribute to optimise economic results since these machines are generally too expensive for individual farmers [21].

3.4. Analysis of different discount rates and biomass prices linked to an evaluation of the internal rate of return (IRR)

Discount rates play a major role when valuing forests and plantations, as highlighted by many authors [71,72]. Choosing the appropriate discount rate is an important factor when choosing the best scenario from among different alternatives [71].

The choice of discount rate depends on the decision-makers [36] and, as stated by Wagner [73], there is no single rate which can be applied for all plantations. This study uses a 5 % real discount rate, although different discount rates were also tested to provide further information on which to base the decisions of investors.

Fig. 6 shows the estimated NPV value for a SRC cycle of 12 years (4 rotations of 3 years) according to possible biomass price and different discount rates under both studied scenarios (Table 1). The resulting rate where the reference lines cut the x-axis for a NPV value equal to zero shows the internal rate of return (IRR) on the investment.

For higher chip biomass prices, the reference lines will take longer to cut the x-axis, obtaining higher IRR values. These results enable managers to compare the investment with alternative investments.

According to the Baseline scenario with an annual biomass productivity of 30.56 Mg ha⁻¹ yr⁻¹ (M ≈ 55 %) and the chip biomass price used in this study (40 € Mg⁻¹), the Diagram-IRR (Fig. 6, top) shows an IRR of around 1 %, which is lower than the discount rate used (5 %). To achieve an IRR above the discount rate used in this study and reach positive NPV values, biomass price should be higher than 43.34 € Mg⁻¹.

In the Optimum scenario (Fig. 6, bottom) with an annual biomass productivity of 56.52 Mg ha⁻¹ yr⁻¹ (M ≈ 55 %) and the chip biomass price used in this study (40 € Mg⁻¹), we reached an IRR of around 27 %, which is substantially higher than in the other scenario. Investors, therefore will see a more attractive investment under this optimum yield scenario.

The IRR provides the decision-maker with useful information, especially as regards quantifying the maximum cost of the capital so that the profitability of investments can be determined [74]. In North America, a financial analysis of poplar plantations showed average IRR values for all the studied scenarios of around 3.58 % [75]. Results of the survey by Manley [76] suggested that in New Zealand IRR is in the range of 4 %–9.2 % with an average of 7 %, while in southern United States it is between 6.4 % and 9.1 % according to Tankersley [77]. In central Europe (Serbia), IRR values for commercial poplar plantations were estimated between 4.3 % and 6.9 % [78]. In Europe, under Mediterranean conditions, some authors have estimated IRR in the range of 2 %–8 % for investments in poplar plantations with lower densities and longer rotations [79]. Under the same Mediterranean conditions, other authors point to opportunities for reasonably attractive investment returns (IRR > 5 %) from forest plantations, particularly for landowners and those in the forest products industry [40], with reported IRR ranging from negative values up to 11.9 % in the best cases [80].

Hauk et al. [8] stated that IRR is not suitable for comparing investments with different upfront costs, which makes it difficult to compare our results with those of others authors, mainly due to the differences in rotation and cycle lengths, densities and cultural operations applied. Fig. 6 shows different IRR values under the Baseline and Optimum scenarios. The IRR is obtained when the reference lines cut the x-axis for a NPV value equal to zero, thus providing a straightforward way to check this factor depending on biomass prices and the real discount rate chosen.

3.5. Simple assessment tool for decision-making

Realistic yield data are essential for evaluating the economic viability of SRC [81]. The need for accurate tools to estimate biomass in poplar SRC has been widely addressed [82–85] and the importance of a real economic analysis has also been studied [8,22,42,81]. This highlights the need to develop an economic analysis based on real data under

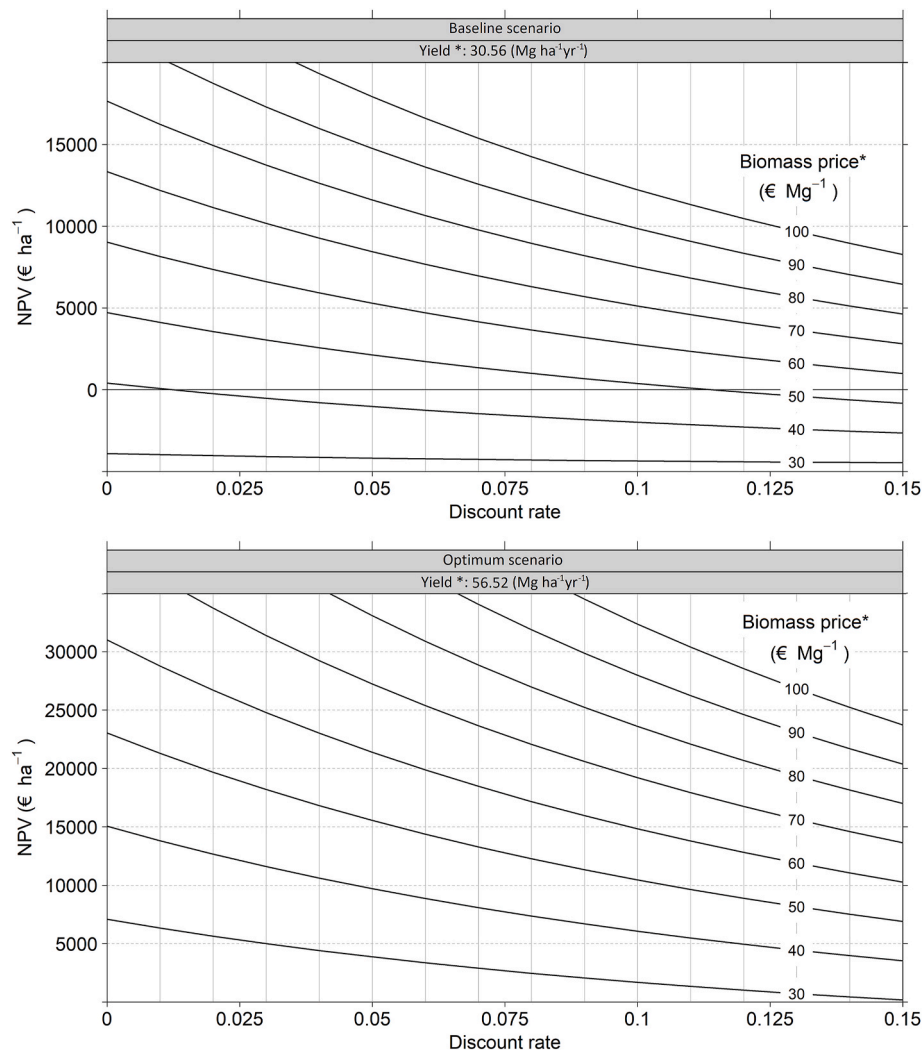


Fig. 6. Relationship between discount rates, biomass prices and NPV in Baseline scenario and Optimum scenario linked to the IRR of the investment. Diagram of IRR (Diagram-IRR). *: $M \approx 55\%$; Cycle: 12-year SRC (4 rotations of 3 years).

Mediterranean conditions which necessitate the use of irrigation systems. Moreover, it is necessary to develop profitability assessment tools for decision-makers which are both easily applied and suited to SRC grown under these climatic conditions. Landowners currently seem to be reluctant to establish SRC, even on marginal land, because of the uncertainty regarding the possible economic returns on their investment [2]. In this regard, we have developed an assessment tool that allows a graphical evaluation of the final NPV achieved from the investment over the 12 year cycle of the poplar SRC according to the chip biomass price scenarios and biomass production expected by the farmers from their land at the end of the 1st rotation with $M \approx 55\%$. This is shown in the Diagram of Productivity and biomass Price (Diagram-PP) in Fig. 7. It should be noted that the discount rate fixed for this diagram was 5% and that the biomass production has been calculated by applying the percentages shown in Table 1.

Analysing our assumed productivity scenarios; in the Baseline scenario (biomass productivity: $30.56 \text{ Mg ha}^{-1} \text{ yr}^{-1}$ with $M \approx 55\%$), the break-even point is reached when the chip biomass price is higher than 43.34 € Mg^{-1} or annual production is greater than $33.23 \text{ Mg ha}^{-1} \text{ yr}^{-1}$ with $M \approx 55\%$. According to the more productive scenario, the Optimum scenario (biomass productivity: $56.52 \text{ Mg ha}^{-1} \text{ yr}^{-1}$ with $M \approx 55\%$), the break-even point is reached when the chip biomass price is higher than 23.52 € Mg^{-1} .

Biomass prices are often a source of uncertainty for investors, as a

range of factors can directly affect them: local demand and supply, distance to facilities or size of the supplier crops, characteristics of the chip depending on its end use, to name just a few. Chip biomass is generally the only source of income while the previously mentioned ecosystem services are not taken into account. If the latter were to be considered then total income would be increased and SRC would be inviting more attractive investment.

The availability of management tools is a key factor in managing this type of plantation. The diagram developed here enables the NPV value for a 12-year SRC cycle under Mediterranean conditions to be calculated, and thus facilitate decision-making based on the benefits that can be obtained at different times depending on the market demands.

The tool developed can be used following a simple procedure to plan and manage irrigated poplar SRC under Mediterranean conditions in accordance with the final objectives desired.

4. Conclusions

Given the appropriate conditions, poplar plantations could be a profitable option for farmers, contributing to a robust, diversified energy mix that takes advantage of complementary renewable energy sources. Poplar plantations also provide offsite-benefits in terms of the bio-economy and reducing harvesting pressure on natural forests.

The findings of this work point to the potential profitability of poplar

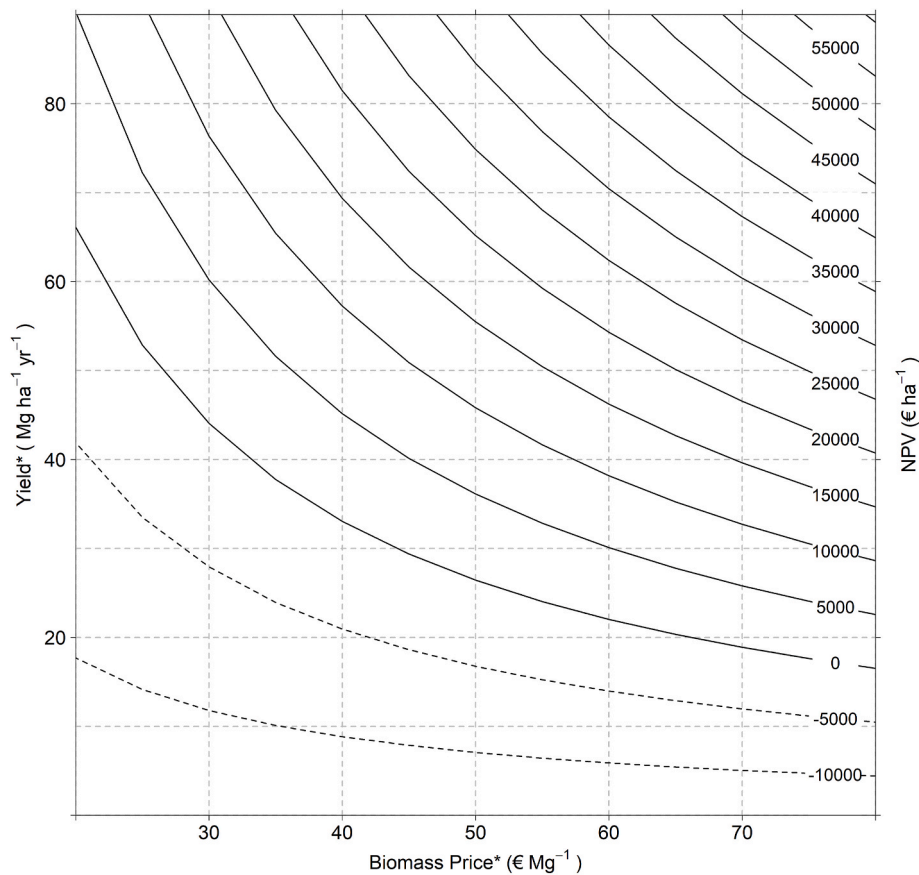


Fig. 7. Diagram of Productivity and biomass Price (Diagram-PP). *: $M \approx 55\%$; Cycle: 12-year SRC (4 rotations of 3 years); Dotted lines in the graphs show negative NPV values.

SRC under Mediterranean conditions (with irrigation) as long as the investment required is accompanied by high productivities and reasonable biomass price thresholds. The critical cost factors are land rental, water and electricity associated with irrigation and cut-and-chip harvesting, the land rental cost being an important factor affecting the profitability of the plantation.

Exploring the possibility of producer associations to mitigate the costs of land rent, developing other methods of irrigation (both in terms of technology and source of the water used) and the introduction of local and associated harvesting options are key to promoting poplar SRC in rural areas of southern Europe. Additionally, it is important to take into account that selecting appropriate genotypes for the site conditions is crucial for optimizing production.

This study reveals that economic viability of poplar SRC will be achieved either by ensuring optimum productivity or through an increase in the market prices, associated with more diversified energy use and/or bioproducts, along with the quantification of ecosystem services, which currently do not have a market price.

The combination of biomass as a raw material for obtaining bio-energy along with the supply of bioproducts could improve economic and resource-use efficiency of biomass and provide additional revenue.

Additionally, a tool for decision-makers is provided that allows the profitability of a poplar SRC with drip irrigation to be evaluated, comparing NPV values derived from different levels of productivity and biomass prices. This tool provides a simple approach for managing SRC in accordance with the final objectives desired.

Credit author statement

Fuertes, A.: Ideas, Formal analysis, Data Curation, Writing - Original Draft, Visualization and Writing - Review & Editing, **Oliveira, N.:** Ideas,

creation of models, Data Curation, Writing - Original Draft, Visualization and Writing - Review & Editing, **Cañellas, I.:** Resources, Writing - Review & Editing, Funding acquisition, **Sixto H.:** Methodology, Conceptualization, Resources, Writing - Review & Editing, Funding acquisition, Project administration and Supervision, **Rodríguez-Soalheiro, R.:** Methodology, Conceptualization, Validation, Writing - Review & Editing, Funding acquisition, Project administration and Supervision.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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