Land Use Policy 76 (2018) 329–337

Contents lists available at ScienceDirect

Land Use Policy

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

Economic assessment of *Eucalyptus globulus* short rotation energy crops under contrasting silvicultural intensities on marginal agricultural land

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ARTICLE INFO

Keywords:
Short rotation woody crops
Bioenergy
Economic evaluation
Monte Carlo
Uncertainty

ABSTRACT

Evolving bioenergy markets requires consideration of marginal lands for woody biomass production worldwide. Growing short rotation woody crops for bioenergy (SRWCs) on marginal land minimizes concerns about using croplands for agricultural production and reinforces sustainability of wood supply. Evaluation of the profitability of marginal land that may have SRWCs potential as sources of biomass for energy production has been rarely reported. This study attempts to account for investments uncertainties on SRWCs production considering *Eucalyptus globulus* managed under contrasting silvicultural intensities on marginal land by comparing four environments and four levels of initial planting density. Our study consider biomass yields over this gradient of productivity and biomass market prices and costs from local contractors. We estimated mean annual above-ground dry biomass increments (MAIs) and evaluated the economic feasibility of various cycles of harvest (2–6 years) using Monte Carlo simulation to examine how uncertainty over the input variables affects NPV of SRWCs. MAIs that ranged 3.91–18.07 Mg ha^{-1} yr^{-1} increased with stand density and harvesting age. Rotation length affected economic outcomes although the returns were poor due to high establishment and maintenance costs, low productivities and low biomass prices. Under an average scenario, current market price of biomass, absence of subsidies and current costs, SRWC are not profitable when productivities are lower than 351 m^3 ha^{-1} of green biomass.

1. Introduction

High dependence on imported fossil fuels and growing demand arising from economic growth has led current Chilean energy policy to mandate a rapid expansion of non-conventional, renewable energy over the coming years. Ley 20.257 (2008) obliges electricity generating companies with an installed capacity of more than 200 MW to commercialize a percentage of energy from non-conventional renewable sources as of January 2010. This percentage has been set to increase from 5 to 10% from 2010 to 2024.

In this scenario, biomass and even bioenergy crops are expected to play an important role in achieving the government's long-term energy objectives. To reach these legal provisions, the government has considered a subsidy for plantations with energy purposes, especially on low-productivity agricultural or marginal lands, known as 'lands of preferably forestry aptitude'.

While several land use categories could be considered as marginal, in general, marginal lands can be broadly categorized as "lands that are not suitable for food-based agriculture and have limited economic potential for fulfilling other ecosystem services" (Shortall, 2013). Conditions that can be attributed to poor physical and chemical soil properties, aridity, and/or susceptibility to erosion (Kang et al., 2013). Biomass production for energy on marginal land minimizes competition with cropland and thus avoids putting pressure on crop and cropland prices (Campbell et al., 2008). Thereby, lignocellulosic feedstocks such as *Eucalyptus* spp. managed in short rotation coppice systems on marginal lands are expected to provide a substantial portion of biomass needed in Chile to achieve renewable energy goals.

Agricultural crops have been widely used as feedstock for energy production (Demirbas, 2009). However, biomass production by dendroenergy crops or short-rotation forest crops are considered a potential solution to mitigate emissions from the electrical and residential sectors to reduce the global dependency on fossil fuel. Nevertheless, the production of biomass based on energy crops has also led to

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https://doi.org/10.1016/j.landusepol.2018.05.028
Received 6 November 2017; Received in revised form 9 April 2018; Accepted 11 May 2018

environmental, social and economic concerns regarding the utilization of arable land (Berndes et al., 2003; Román-Figueroa and Paneque, 2015).

Short-rotation forest crops dedicated to energy production, in addition to not competing for land used for food production, may represent a great opportunity to stimulate local economic development, restore degraded soils or their ecological characteristics and reduce the emission of greenhouse gases (Esquivel et al., 2013; Semere and Slater, 2007; Tilman et al., 2006).

The central-southern part of Chile is occupied with plantations of *Pinus radiata* and *Eucalyptus* spp., and the area of plantations of the latter genus has been increasing in recent years. Theoretically, an area of SRWC plantations can be established because the amount of land that meets the criteria for wood energy crops (without competing with or negatively impacting food production) is estimated to be 9908 km^2 between the regions of Libertador Bernardo O'Higgins and Biobío (INFOR, 2016).

The main characteristic of wood energy crops is their lower rotation age compared to traditional crops. Moreover, the forester can choose fast-growing species to regrow, and thus save on establishment costs for future rotations. Regrowth in some species may even present higher growth rates than the initial plantation (Sixto et al., 2007). Thus, the implementation of this type of crop depends on several factors such as supply chain infrastructure, degree of sustainability and financial viability (Bauen et al., 2009), with the latter the principal condition that must be met for landowners to become interested in establishing SRWC.

The economic efficiency of this type of production, like any other, depends mainly on the supply and demand for this type of energy raw material, competing with the biomass residual of forest harvesting (Acuña et al., 2017). In addition, the profitability of SRWC biomass production is strongly correlated with crop yield. The dry matter yield of *Eucalyptus globulus* cultivated under experimental conditions in low fertility soils reaches 15 Mg ha^{-1} $year^{-1}$ (Sandoval, 2012). This is because farmers will establish SRWC plantations on lower quality soils whose use for food crops and livestock feed is minor or limited, which is perfectly understandable and justified, as good quality soils are used for food crop production.

In Chile, SRWC for bioenergy are still at an experimental level, and experiences have been focused mainly on degraded or marginal agricultural land not suitable for food production. SRWC have been identified as a strategy for carbon sequestration and emission reductions strategies at a national level, and like other parts of the world, biomass energy projects have encouraged governmental subsidies for the establishment of this type of crops with emphasis on *Eucalyptus*. However, there are still few studies that evaluate the growth and biomass yield across sites at the local level, but more importantly, and missing from overseas research, provide an analysis of the potential profitability, economic assessments or financial feasibility of these promising SRWC proposed as an economic option for small landowners (Acuña et al., 2012).

This study analyzes the key variables that affect the economic sustainability of *E. globulus* SRWCs for energy purposes under contrasting silvicultural intensities on marginal agricultural land.

2. Methods

2.1. Description of the study area

The study considered information from four contrasting productivity soil-site environments in central-south Chile, i.e. Parcelas Collipulli (high fertility non-irrigated, HFni) (38.1238 °S, 72.1053° O) located in the southern foothills of the Andes mountains (580 m asl), Santa Leonor (medium fertility non-irrigated, MFni) (36°42′14″ S; 72°16′35″ W), Santa Rosa (low fertility non-irrigated, LFni) (37°03′33″ S; 72°11′12″ W) and Carlos Douglas (low fertility irrigated, LFir) (37.1335 °S, 72.4685° O).

All south-central valley sites have a flat terrain topography but showed contrasting soils and land past use. The southern HFni site was previously occupied by a 24-year-old *P. radiata* plantation, had a mean annual rainfall of 1324 mm and minimum, mean, and maximum mean annual temperatures of 5.3 °C, 11.3 °C, and 17.5 °C, respectively. Soils are Santa Bárbara soil family series derived from recent (8000–10000-years-old) volcanic ash and are classified as a mesic Typic Haploxerand (Andisol). Soils are deep (> 150 cm), well drained and structured, and show a loamy or silt loamy surface horizon and silt loam texture in depth (CIREN, 1999a). The MFni site was previously used for grazing, had a mean annual rainfall of 877 mm and minimum, mean, and maximum mean annual temperatures of 6.6 °C, 13.5 °C, and 19.8 °C, respectively. Soils are Bulnes soil series (CIREN, 1999b) derived from old volcanic ash and are deep (> 150 cm) with clay loam textures with gravel and stones in depth. Soil bulk density varies between 1500 to 1900 kg m^{-3}, mean soil reaction is pH = 6.4 and a 4.2% organic matter content. The LFni site previous use was a 22-year-old *Pinus radiata* D. Don plantation, had a mean annual rainfall of 1048 mm and minimum, mean and maximum mean annual temperatures of 6.4 °C, 12.9 °C and 19.3 °C, respectively. Soils are Coreo soil series (CIREN, 1999b) derived from andesitic and basaltic sands, deep (> 150 cm) and with surface loamy texture and deep coarse sandy soil texture in depth. Soils show a slightly acidic soil reaction pH = 6.0, with concentration of salts such as calcium, magnesium, sodium and potassium. Soil are deficient in iron, manganese, copper, zinc, boron and other minerals, and organic matter and nitrogen are low. The LFir site, previously used for radiata pine seedlings production, had a mean annual rainfall of 990 mm and minimum, mean and maximum mean annual temperatures of 7.0 °C, 12.7 °C and 19.7 °C, respectively. Soil belong to Arenales soils series (CIREN, 1999b) which is a member of the mixed thermal family of Dystric Xeropsamments (Entisol). Soils are alluvial sediments with deep (> 150 cm) underdeveloped soils derived from volcanic black sands from andesitic and basaltic origin.

2.2. Experimental design and treatments

Four trials, configuring a gradient of site productivity, were established to evaluate the effect of the planting density on maximizing biomass production of *E. globulus*. In order to facilitate plant development and productivity at each site, for all sites, except for HFni (for details see Albaugh et al. (2017), soil preparation considered subsoiling after removal of previous rotation harvesting residues. Subsoiling at 80 cm depth was performed in a square grid design considering 60 cm distance between rows using a Caterpillar D8K bulldozer. After planting each seedling was fertilized with 30 g of N, 20 g of P, and 3 g of boron, applied at 20 cm from the planting hole over ground. Fertilizer sources considered urea, triple superphosphate and boronatrocalcite. Chemical weed control was applied before and after planting (1st year) using 2.0 kg ha^{-1} of glyphosate. Protective screens were used to avoid herbicide drift.

For HFni and LFni trials *E. globulus* was established and compared with two additional species, *Eucalyptus nitens* Maiden and *Acacia melanoxylon* R.Br. The experimental design considered a complete block randomized design with three replicates, considering species as the main factor and three levels of initial planting density (5000, 7500 and 10,000 trees ha^{-1}). Each block (5625 m^2) had nine experimental units of 25 × 25 m (625 m^2) with 8 m buffers at each side, and considered 49 trees as measurement plot. At the MFni site the same species were tested, but initial planting density was constant (15,000 trees ha^{-1}). The experimental design considered three blocks with five experimental units of the same size than other sites. In each experimental unit, a different species was established considering similar weed control and fertilization rates to secure appropriate establishment of seedlings. At LFir site, considering the lack of fertility of this site, soil preparation considered a 30 cm plowing system and pre-planting and post planting weed control during the first year to provide a free weed competition areas (2 times application). In order to maximize biomass accumulation, during winter time after the first year of planting, all established trees were cut and sprouts were managed with fungicide applications, and additional weed control (glyphosate) was applied until canopy closure. To reduce site nutrient and water limitations, and to understand potential productivity under these limited sites, a fertirrigation treatment was applied between October and May (650 mm) of each year considering all macro and micro nutrients applied.

Annual measurement of total height and ground line diameter (D) at 0.1 m above ground level were obtained, and when trees exceeded 1.3 m in height, diameter at breast height (DBH) was included. To assess biomass at different stage of development at each site during July of each year, destructive samples were extracted cutting three trees per experimental unit from buffer areas. Threes were selected to represent the diameter (D or DBH) and height distribution of each treatment. Each tree biomass components were separated (leaves, branches, trunk and roots) and dry weight measured were obtained (Sandoval, 2012). Allometric biomass regressions equations were developed to estimate biomass components (foliage, branch, stem and root) across all treatments for each species and plot biomass estimates were scaled considering plot size. Analyses testing for site and planting density differences in regression models were considered when needed to adjust for these factors on biomass estimates. All statistical analyses were carried out using software SAS V9.4 (SAS Institute Inc. Cary, NC).

2.3. Economic assessment

Using all information obtained from biomass accumulation (Mg ha^{-1}) at each site, a deterministic and stochastic assessment analysis was performed through the method of the discounted cash flow (DCF). The economic model took in account from establishment of the SRWC to the sale of the biomass at farm gate. Economic evaluation criteria were used to assess initial stand density treatments at all sites and considered the last measurement performed at each cycle of harvest or rotation age. Analysis considered 18 and 20 year lifespan horizon evaluations, with harvesting cycles from 2 to 6 years. No higher yields were attributed after the first harvest, assuming the same yields at each harvest cycle. Field operational costs corresponding to each silvicultural activity and their timing of application are presented in Table 1.

Two economic assessments were carried out. The first did not consider subsidies, addressing the costs of the sylvicultural activities presented in Table 2 and the incomes from the sale of biomass ($ Mg^{-1}). The second evaluation considered the subsidy granted by Decree Law N° 701, specified in the Table of General Foresting Costs for plantations with energy uses (CONAF, 2011). This subsidy is only granted to the genus *Eucalyptus* plantations.

2.3.1. Deterministic assessment

Deterministic assessment allowed obtaining the profitability indicator of the maximum net present value (NPV) associated to each site (equation 1), where a value higher than zero in the NPV will represent a positive profitability of the project. For all estimates a 0% annual inflation was considered for the NPV and DCF valuation. NPV was estimated considering the following expression:

$$NPV = \sum_{t=0}^{n} (1 + r)^{-t} \times A_t, \tag{1}$$

where t is the time in years, n is the assessment horizon of the project, r is the cost of the capital or discount rate (8%), and A_t is the net cash flow for year t. Another calculated profitability indicator is the equivalent annual value (*EAV*), which converts costs and benefits in equal annual amounts during the project evaluation period by combining annuity and NPV methods (equation 2).

$$EAV = \frac{r}{(1 - (1 + r)^{-t})} \sum_{t=0}^{n} (1 + r)^{-t} \times A_t \tag{2}$$

The internal rate of return was not calculated because this indicator can provide a biased image of the profitability of the plantation if subsidies to the establishment of plantations are taken into account (Bell et al., 2007).

Table 1
Investment and production costs.
Source: Local contractors, forest companies, governmental subsidies (CONAF, 2011).

Item	Year of operation	Value	Unit
Subsoiling	0	195.84	\$ ha^{-1}
Site preparation residues	0	156.07	\$ ha^{-1}
Seedlings acquisition	0	0.08	\$ Unit^{-1}
Density 5000	0	475.65	\$ ha^{-1}
Density 7500	0	713.47	\$ ha^{-1}
Density 10,000	0	951.29	\$ ha^{-1}
Density 15,000	0	1,426.94	\$ ha^{-1}
Manual planting 5000	0	334.44	\$ ha^{-1}
Manual planting 7500	0	501.66	\$ ha^{-1}
Manual planting 10,000	0	668.88	\$ ha^{-1}
Manual planting 15,000	0	1,003.31	\$ ha^{-1}
Chemical weed control (Pre and post planting) 5000, 7500, 10,000, 15,000	0	118.91	\$ ha^{-1}
Fertigation system installation	0	3,210.61	\$ ha^{-1}
Fertigation (annual) 5000	Each year	119.64	\$ ha^{-1}
Fertigation (annual) 10,000	Each year	158.81	\$ ha^{-1}
Fertilization (Pre and Post planting) 5000	1st year and onwards in the 1st year of each harvest cycle	101.92	\$ ha^{-1}
Fertilization (Pre and Post planting) 7500	1st year and onwards in the 1st year of each harvest cycle	142.69	\$ ha^{-1}
Fertilization (Pre and Post planting) 10,000	1st year and onwards in the 1st year of each harvest cycle	178.37	\$ ha^{-1}
Fertilization (Pre and Post planting) 15,000	1st year and onwards in the 1st year of each harvest cycle	274.42	\$ ha^{-1}
Administration	Each year	3.72	\$ ha^{-1}
Harvesting cost	Each rotation period	10.65	\$ Mg^{-1}
Market price biomass	–	26.50	\$ Mg^{-1}
Conversion factor	–	6.00	Loose m^3 to Mg dry biomass
Price per loose cubic meter	–	3.74	\$ m^{-3} loose green biomass
Subsidy seedlings acquisition	1	1,103.83	\$ ha^{-1}
Subsidy soil preparation (subsoiling)	1	104.28	\$ ha^{-1}
Subsidy fence preparation	1	177.22	\$ ha^{-1}

Table 2
The assumptions on the data in the simulation sets.

Data	Units	Assumptions made and data source
Growing stock	Mg ha^{-1}	According to Sandoval et al. (2012) a Weibull distribution function for the variation in crop productivity was defined.
Prices	$ ha^{-1}	Most of the cost items were associated with a triangular probability distribution considering minimum and maximum values from local forest companies and contractors. The use of triangular distributions allowed to compensate for the inexistence of standard deviation of distributions, a key component of normal distribution curves (Moore et al., 2012).
Production costs	$ ha^{-1}	Income and costs were considered perfectly correlated for a given period (Klemperer, 1996). In that case, the same probability distribution was applied to this risk factor taking modal values provided by local contractors
Harvesting cost	$ Mg^{-1}	A triangular distribution was used considering data provided by local contractors.
Discount rate	Dimensionless	A reduction of the discount rate was used from the point of view of intergenerational equity, given the length of the forest project (Hepburn and Koundouri, 2007). Using data provided by forest companies an uniform distribution was considered (Woolf et al., 2016)
Conversion factor	Loose m^3 to Mg dry biomass	For biomass material commercialization conversion factor between dry weight and green volume is highly relevant considering the measurement unit of raw material and its moisture content. Data from Cancino and Acuña, 2012 unpublished) was used considering a triangular distribution (Shabani and Sowlati, 2016).

2.3.2. Stochastic assessment

To represent the results of the stochastic evaluation, the treatment that obtained the highest deterministic NPV was used. Palisade's @Risk 7.5.1 software was used to run Monte Carlo simulation (Lopez et al., 2017; Yemshanov and McKenney, 2008; Yemshanov et al., 2005). The value drivers identified from the project's sensitivity analysis were selected as the input variables. To account for uncertainty in these value drivers, suitable probability distribution functions (PDF) were assigned. Variables subject to uncertainty treated in the Monte Carlo simulation are presented in Table 2. Parameters ranges were established using local contractors costs similar to Dias et al. (2009) and Kallio (2010). Monte Carlo simulation was carried out for the most profitable site-planting density treatment with and without subsidies. In order to calculate the probability distribution for NPV, 1500 iterations were run following the methodology proposed by Gottfried (1984).

3. Results

3.1. Biomass growth

Cumulative biomass yield varied among sites and stand densities. As expected, *E. globulus* accumulated higher total biomass per hectare at fertile sites. The smallest growth was recorded at the poorest fertility and low water holding capacity site but the same soils were one of the most productive sites when fertigation was applied (Fig. 1).

3.2. Deterministic economic assessment

Result of the DCF, NPV and EAV associated to each treatment were obtained from non-subsidized and subsidized assessments (Table 3). All treatments from the non-subsidized assessments showed a negative NPV value. In fact, the most profitable treatment, closest to zero (−8.92 $ ha^{-1}), was for *E. globulus* established at 5000 trees ha^{-1} planting density at the HFni site, with an equivalent annuity of −0.91 $ ha^{-1}.

As a result of the damping of the initial investment with the subsidy value paid after verifying the requirements for plantations whose objective is the production of biomass for energy generation (CONAF 2011) – only MFni does not achieve positive VPN, being *E. globulus* at 5000 trees ha^{-1} treatment greatest positive results. The highest NPV value was obtained by *E. globulus* with 1273.78 $ ha^{-1} considering harvesting cycles every 5 years.

Discounted costs from establishment of *E. globulus* SRWC at 5000 trees ha^{-1} are presented in Fig. 2. Harvesting and planting costs play important roles in limiting the potential profitability of biomass production. The most important costs at time of planting included seedlings and manual planting (475.65 and 334.44 $ ha^{-1}, respectively), which accounted by 30% of total costs. Initial number of seedling is one of the main financial constraints for establishing SRWC at high planting densities. At the end of the rotation period, harvesting accounted by 40% of total costs (1022.39 $ ha^{-1}). However, harvesting costs do not depend on initial planting density.

Discounted annual cash flow, cumulated cash flow and crop annuity are presented in Fig. 3 for subsidized and non-subsidized conditions. Under non-subsidized conditions, discounted flows are not capable of recovering the costs during the project life cycle (Fig. 3A). For subsided conditions, the payback is achieved at five years -first rotation. Establishment cost levels and the biomass price in a non-subsidized scenario

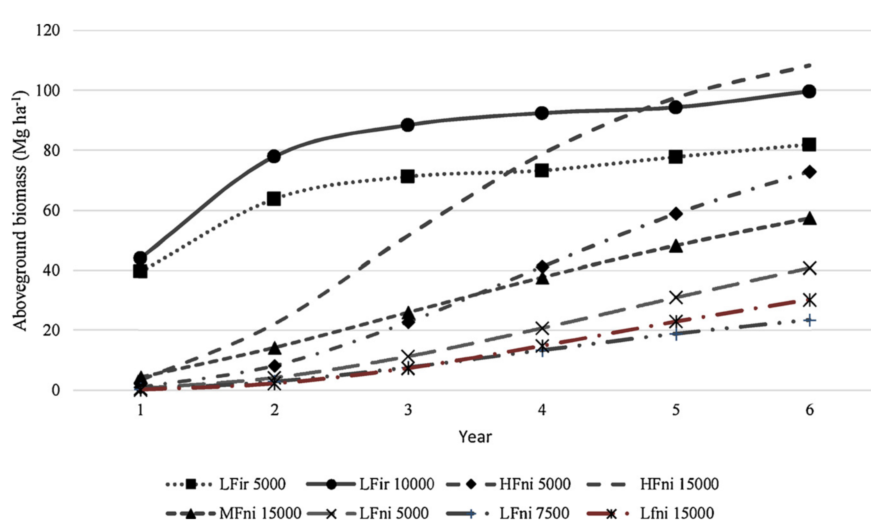

Fig. 1. Cummulative total dry aboveground biomass yield over time (Mg ha^{-1}).

Table 3
Results from the deterministic economic assessment.

Parameter	Planting density (tree ha^{-1})	Rotation (year)	HFni		MFni		LFni		LFir	
			without subsidy	with subsidy	without subsidy	with subsidy	without subsidy	with subsidy	without subsidy	with subsidy
NPV	5000	2	−1725.62	−442.92			−1427.52	−144.81	−237.87	1044.84
		3	−1111.42	171.29			−932.83	349.87	−816.30	466.40
		4	−444.61	838.10			−521.18	761.53	−1881.58	−598.87
		5	−8.92	1273.78			−309.97	972.73	−2856.80	−1574.09
		6	−71.12	1211.59			−345.56	937.15	−3580.97	−2298.27
	7500	2					−2239.89	−957		
		3					−1823.21	−541		
		4					−1573.42	−291		
		5					−1411.18	−128		
		6					−1393.77	−111		
	10,000	2					−2901.18	−1,618	−732.18	550.53
		3					−2329.69	−1047	−1702.38	−419.67
		4					−2008.72	−726	−3044.74	−1762.03
		5					−1818.47	−536	−4044.89	−2762.19
		6					−1790.74	−508	−4753.63	−3470.92
	15,000	2	−3271.53	−1988.82	−3434.95	−2152.24				
		3	−2131.09	−848.39	−2694.53	−1411.83				
		4	−1364.78	−82.07	−2336.76	−1054.05				
		5	−1048.51	234.20	−1996.64	−713.94				
		6	−1149.68	133.03	−1978.99	−696.28				
EAV	5000	2	−175.76				−145.40	−14.75	−24.23	106.42
		3	−118.59	18.28			−99.54	37.33	−87.10	49.77
		4	−45.28	85.36			−53.08	77.56	−191.64	−61.00
		5	−0.91	129.74			−31.57	99.07	−290.97	−160.32
		6	−7.59	129.28			−36.87	100.00	−382.10	−245.23
	7500	2					−228.14	−97.49		
		3					−194.54	−57.67		
		4					−160.26	−29.61		
		5					−143.73	−13.09		
		6					−148.72	−11.85		
	10,000	2					−295.49	−164.85	−74.57	56.07
		3					−248.58	−111.72	−181.65	−44.78
		4					−204.59	−73.95	−310.11	−179.47
		5					−185.22	−54.57	−411.98	−281.33
		6					−191.08	−54.21	−507.22	−370.35
	15,000	2	−333.21	−202.57	−349.86	−219.21				
		3	−227.39	−90.52	−287.51	−150.64				
		4	−139.01	−8.36	−238.00	−107.36				
		5	−106.79	23.85	−203.36	−72.72				
		6	−122.67	14.19	−211.16	−74.29				

make SRWCs not economically feasible (Fig. 3A).

The comparative break-even analysis calculated the price and yield of biomass that would be necessary for the producer to obtain a net benefit of the biomass energy crop. The results show that biomass prices delivered at the farm gate above 28.13 $ Mg^{-1} dry biomass and 351 m^3 ha^{-1} of green biomass (MAI of 11.8 Mg dry biomass ha^{-1} $year^{-1}$), would make viable SRWCs without any state incentives (subsidies).

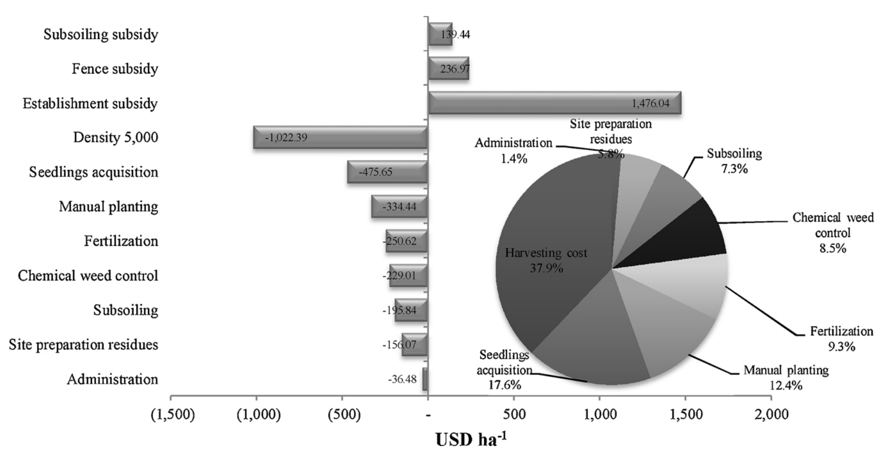

Fig. 2. Discounted costs and revenues by subsidy, and costs distribution discounted at the establishment of 5000 trees ha^{-1} at HFni site (bars indicate absolute values, whereas the circular chart shows values in percentage).

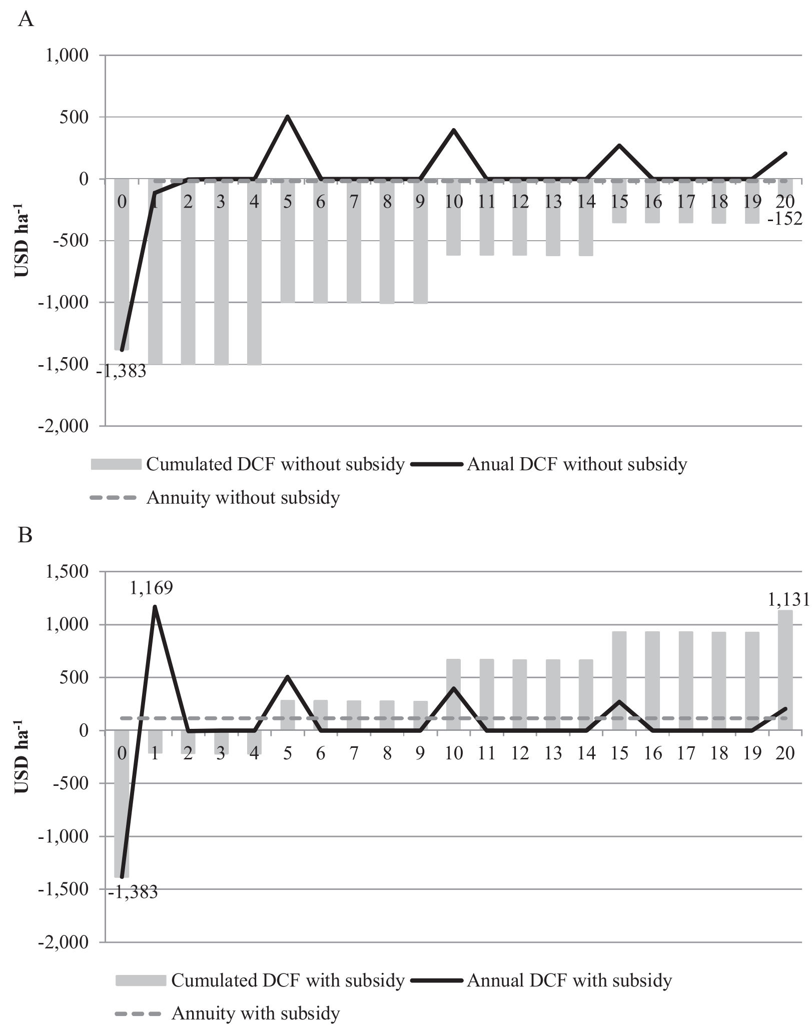

Fig. 3. Discounted cash flow, cumulated discounted cash flow and reference annuity for establishment of 5000 trees ha^{-1} at HFni site. A) non-subsidized condition; B) subsidized condition.

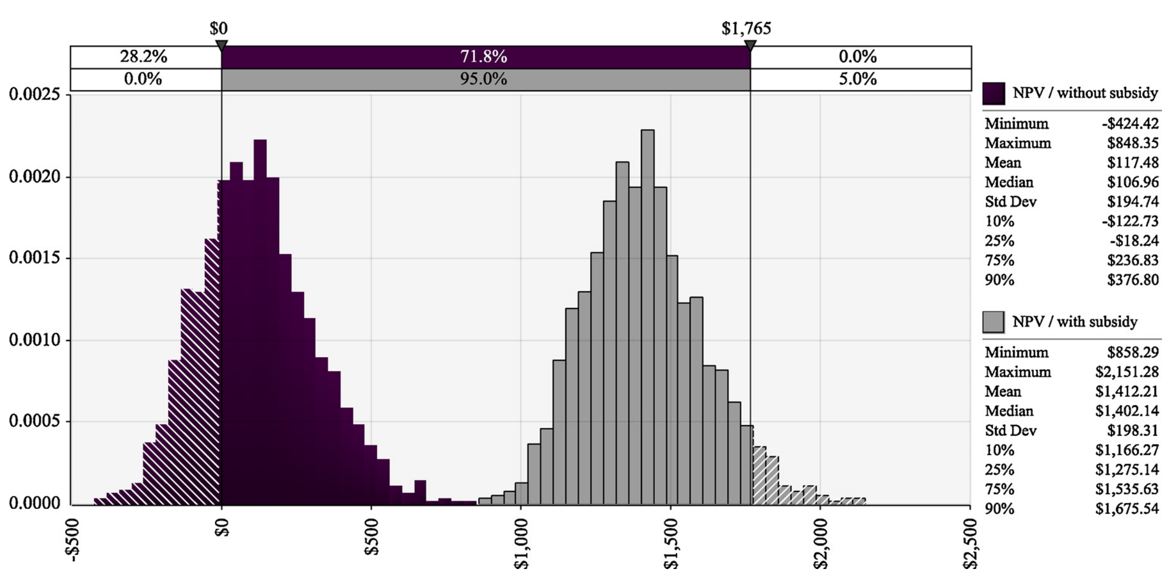

Fig. 4. NPV probability distribution considering the establishment of 5000 trees ha^{-1} at HFni site with and without subsidized conditions.

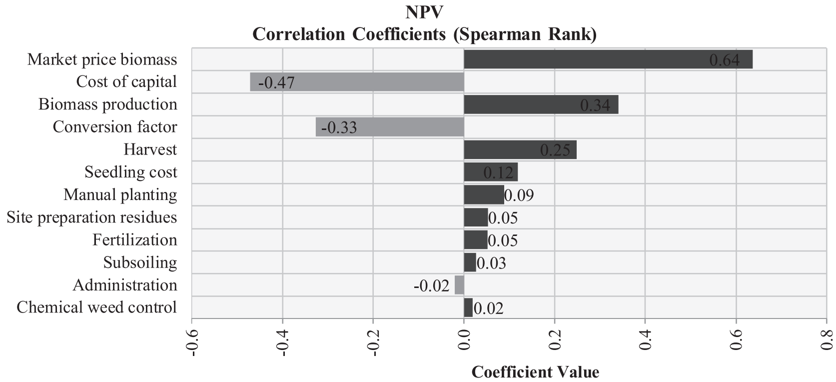

Fig. 5. Correlation analysis among NPV and uncertainty variables for the assessment of the establishment of 5000 trees ha^{-1} at HFni site without subsidized conditions.

3.3. Stochastic assessment

Considering the variability of inputs used in the Monte Carlo simulation, there was a 28.7% probability that NPV achieved a negative result for no subsidized conditions (Fig. 4). The expected median NPV value ranged from 109.07 for non-subsidized and 1402.65 $ ha^{-1} for and subsidized plantations.

According to Talavera et al. (2011), the sensitivity analysis allows to study the impact of the independent variables of a model where uncertainty may affect the final results. The sensitivity analysis enriches a simple economic evaluation because it provides a range of values rather than a single value, allowing a more complete analysis and verifying positive and negative scenarios. The most critical factors resulting from the Monte Carlo sensitivity analysis are presented in Fig. 5.

The average cost of delivered dry biomass was estimated in 26.5 $ Mg^{-1}. On the other hand, the estimated cost of the green biomass is based on the cost per loose cubic meter (3.74 $ m^{-3}) at the farm gate. Although that a most likely conversion factor of 6.0 cubic meters per dry Mg was used in the analyses, there is an expected distribution that follows a triangular distribution for this factor. The adjustment of the distribution model considered the adjustment of a distribution function from the @Risk software. Correlation range determined how uncertainty variables of the model influenced NPV outcome (Fig. 5).

To provide a more exhaustive economic assessment of SRWC eucalyptus biomass plantations, a sensitivity analysis has been carried out. Scenarios for wood biomass price were evaluated considering 10% above and below its baseline value. Sensitivity analysis showed that a decrease of 10% of wood biomass price would cause a mean annual cash flow to drop −91.77 $ ha^{-1}. Conversely, a 10% price increase will increase mean annual cash flow to 331.59 $ ha^{-1}.

Discount rate ($\rho = -0.47$) ranked second and biomass production ($\rho = 0.34$) ranked third on NPV impact uncertainty variables. Unexpectedly the conversion factor from loose cubic meter to Mg dry biomass, ranked four showing a positive correlation coefficient $\rho = 33$ (Fig. 5).

4. Discussion

Our study allowed to provide insights on the economic evaluation of *Eucalyptus globulus* as a representative and potentially most attractive SRWC considering a broad range of minimum and maximum attainable productivities. The results of the present study suggest that *E. globulus* cultivated in high fertility non-irrigated sites but under soils with high water holding capacity reached the highest biomass production. Conversely, *E. globulus* planted in low fertility non-irrigated sites had the lowest growth figures of those analysed.

The deterministic economic evaluation criteria used to assess initial stand density treatments at all sites and at each cycle of harvesting or rotation age, showed that all sites and treatments considering non-subsidized conditions showed a negative NPV value. Considering the potential advantages of producing biomass on marginal lands (lower land cost and stumpage price) - the chief potential disadvantage is lower productivity. As a result, the price of wood biomass is the most important factor to obtain economic gains from SRWCs (Krasuska and Rosenqvist, 2012).

The Monte Carlo simulation highlighted values of our *Eucalyptus* SRWC significantly lower respect to the annual cash flow of a traditional forest plantation crop estimated by Cubbage et al. (2014) for *P. radiata* (680 $ ha^{-1} at a poor site) or for *E. globulus* for pulpwood (1804 $ ha^{-1}). Sensitivity analyses showed that to obtain a SRWC annual cash flow equivalent to a traditional forest plantation, the sales price of biomass should reach a value of 35.21 $ Mg^{-1}, which will require an increase on its current market price of 32.7%. Simulations highlighted that introduction of *Eucalyptus* SRWC as a local crop competing traditional plantations only with a substantial increase on sale price of biomass by introducing subsidies. Government subsidies are required given the high initial investments of SRWCs that affect cash flow structure.

Similar results have been found for short rotation willow crops by Vandenhove et al. (2002) in Belarus, Ericsson et al. (2006) in Poland, Goor et al. (2000), Styles et al. (2008) in Ireland, Witters et al. (2009) in Belgium, Buchholz and Volk (2011) and Buchholz and Volk (2013) in the United States, and in *Populus* SRWC by Tharakan et al. (2005) in United States, Gasol et al. (2009) in Spain, (Manzone et al., 2009) in Italy and Faasch and Patenaude (2012) in Germany. These authors state that the biomass price, crop yield, efficient harvesting extraction systems and government subsidies, are the key variables of impact to make this kind of crops long-term viable.

Past studies have claimed that using marginal lands to produce bioenergy is unfeasible due to lack of economic incentives (Bryngelsson and Lindgren, 2013). Based on the results of our study, current subsidies will not allow the establishment of SRWC highly attractive under current market conditions. Subsidies sometimes are also inefficient because they take the form of fixed payments, independently of attained biomass yield. In order to solve this, the introduction of CO_2 emission trading for commercial biomass production projects could contribute to alleviate this situation and provide an additional incentive to optimize operational efforts (Tao et al., 2017). This market instrument can become an economically efficient alternative because the emission trading provides incentives to produce higher biomass levels, as it paid per every non-emitted Mg of CO_2. However, the reduction of CO_2 emissions as a result of using biomass in replacement of fossil fuels are not included in our analysis and strong quantitative analyses will require a life cycle analyses approach in order to appropriately integrate all C inputs and outputs (Morales et al., 2015).

To reach government scenarios, it is recommended to improve the subsidies sufficiently, efficiently and coherently considering that Chile committed a set of mitigation measures such as: to reduce by 2030 its CO_2 emissions by 30% in relation to the floor of the year 2007, to recover 100 thousand hectares of forests and to reforest an additional 100 thousand.

5. Conclusions

Under the average scenario (current market price of wood biomass, absence of subsidies, average level of costs and cost of capital), SRWC are on the bound not profitable when the conditions of the site are low fertility (marginal agricultural land). Political instruments and more favorable economic conditions such as higher subsidies, lower costs and higher prices of biomass can lead to higher profitability of SRWC. In conclusion, SRWC would be a viable alternative with a substantial increase of sales price of wood biomass or introducing more efficient subsidies.

Acknowledgments

This work was supported by the Chilean National Commission for Scientific and Technological Research with a FONDECYT grant N° 1140482 "Sustainability of water and nutrient use in short rotation woody crops for bioenergy" and also included data supported by project Innova Bio Bio N° 06-PC S1-33 "Desarrollo de protocolos para la producción de biomasa de especies forestales de rápido crecimiento y corta rotación para la generación de bioenergía". The authors would like to acknowledge the technical and financial support from the forestry enterprises Masisa Forestal S.A. and Forestal Mininco S.A.

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