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

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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 aboveground 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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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