Universidad de Concepción
Dirección de Postgrado
Facultad de Ciencias Forestales - Programa de Magister

MODELACION DEL CRECIMIENTO BASADO EN PROCESOS y EFECTOS POTENCIALES DEL CAMBIO CLIMATICO EN PLANTACIONES DENDROENERGÉTICAS DE *Eucalyptus globulus* Labill.

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Concepción - Chile
2019

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Agradecimientos

Esta investigación fue realizada como parte del proyecto FONDECYT 1140482 "Sustainabylity of water and nutrient use in short rotation Woody crops for bioenergy" y con el apoyo de los laboratorios de biomasa y bioenergía y el de Suelos, Nutrición y Productividad Forestal Sustentable de la Facultad de Ciencias Forestales.

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RESUMEN GENERAL

Los recursos renovables cumplen un rol fundamental en el desarrollo de la bioenergía y las plantaciones de corta rotación prometen ser una fuente de materia prima para la producción de energía renovable. El principal paso para la evaluación de estas plantaciones es la determinación del potencial productivo bajo diferentes condiciones de manejo y establecimiento junto con la determinación de potenciales efectos del cambio climático sobre la productividad de estas plantaciones. La forma adecuada de evaluar una plantación cuando solo se dispone de información edafoclimática es mediante modelos basados en procesos. El modelo parametrizado con mayor frecuencia en la literatura es el modelo 3-PG. Este modelo utiliza como información primaria el clima; suelo; parámetros específicos de la especie y el estado inicial de simulación, obteniendo como resultado información dasométrica detallada. Este modelo fue parametrizado con el objetivo de estimar la biomasa aérea en plantaciones de corta rotación con fines energéticos de *Eucalyptus globulus*. Se obtuvieron parámetros específicos para la especie en la zona centro sur de Chile, considerando niveles de densidad de establecimiento de 5000, 10000 y 15000 árboles ha^{-1} y sitios de alta fertilidad natural y baja fertilidad natural con fertirrigación en periodos estivales. El modelo 3-PG fue eficiente en la determinación de la biomasa aérea de estas plantaciones ($RMSE$ varió de 2,6 − 6,5 $Mgha^{-1}$). Ademas, nuestros resultados sugieren que la acumulación de biomasa aérea no es afectada por la densidad de establecimiento rotaciones de 4 años. No obstante, el diámetro promedio del rodal y la proporción de la biomasa del follaje en la cosecha fueron afectados tanto por el sitio y la densidad de establecimiento. La aplicación de esta herramienta al análisis del potencial productivo del suelo en el centro de Chile, junto con los niveles estimados de biomasa aérea (83 y 115 $Mgha^{-1}$), sugiere que este tipo de plantaciones podría ser atractivo para los agricultores y empresas forestales y eléctricas.

Al evaluar el efecto del cambio climático sobre la productividad de plantaciones de corta rotación con fines energéticos de *E. globulus*, se ha concluido que el efecto del aumento en los niveles de CO_2; la reducción de las precipitaciones y un aumento de la temperatura promedio afectan positivamente la acumulación de biomasa aérea.

GENERAL ABSTRACT

Renewable resources play a fundamental role in the development of bioenergy and short rotation plantations promise to be a source of raw material for the production of renewable energy. The main step for the evaluation of these plantations is the determination of the productive potential under different conditions of management and establishment along with the determination of potential effects of climatic change on the productivity of these plantations. The proper way to evaluate a plantation when only edaphoclimatic information is available is through process-based models. The most frequently parameterized model in the literature is the 3-PG model. This model uses climate as primary information; ground; specific parameters of the species and the initial state of simulation, obtaining as a result detailed dasometric information. This model was parameterized with the objective of estimating the aerial biomass in plantations of short rotation with energetic ends of *Eucalyptus globulus*. Specific parameters were obtained for the species in the south central zone of Chile, considering levels of establishment density of 5000, 10000 and 15000 trees ha^{-1} and sites of high natural fertility and low natural fertility with fertigation in summer periods. The 3-PG model was efficient in the determination of the aerial biomass of these plantations ($RMSE$ varied from 2.6 to 6.5 $Mgha^{-1}$). In addition, our results suggest that the accumulation of aerial biomass is not affected by the establishment density rotations of 4 years. However, the average diameter of the stand and the proportion of the biomass of the foliage in the harvest were affected by both the site and the density of establishment. The application of this tool to the analysis of the productive potential of the soil in central Chile, together with the estimated levels of aerial biomass (83 and 115 $Mgha^{-1}$), suggests that this type of plantation could be attractive to farmers and forest and electric companies. In assessing the effect of climate change on the productivity of short-rotation plantations for *E. globulus* energetic purposes, it has been concluded that the effect of the increase in CO_2 levels; the reduction of rainfall and an increase in average temperature positively affect the accumulation of aerial biomass.

INTRODUCCIÓN GENERAL

El mundo ha experimentado un incremento continuo de demanda energética que es satisfecha fundamentalmente por combustibles fósiles (*Carroll and Somerville*, 2009; *IPCC*, 2007). Las externalidades ambientales de la producción de energía en base a combustibles fósiles, sumado a la incertidumbre de su abastecimiento futuro y el aumento constante en el costo de extracción y transformación, sitúan a las energías renovables a partir de biomasa dentro de las alternativas de producción sustentable de energía (*Goldemberg and Coelho*, 2004; *King et al.*, 2013). Las políticas futuras requerirán, en el mediano y largo plazo, el uso de materias primas renovables para la producción de energía o combustibles líquidos; estableciendo estándares de producción y eficiencia junto con incentivos para el establecimiento de plantaciones con fines energéticos (*CONAF*, 2015; *Sissine*, 2007). En general, los cultivos agrícolas han sido ampliamente utilizados como materia prima para la producción de energía (*Demirbas*, 2009). Sin embargo, plantaciones forestales de corta rotación y altas densidades destinados a la producción de energía, además de no competir por tierra destinada a la producción de alimentos (*Giampietro et al.*, 1997), representan una gran oportunidad debido a que pueden: estimular el desarrollo económico local, restaurar suelos degradados o sus características ecológicas (*King et al.*, 2013; *Semere and Slater*, 2007; *Tilman et al.*, 2006), y reducir la emisión de gases de efecto invernadero (*Esquivel et al.*, 2013).

En este escenario, los plantaciones forestales con fines energéticos, o también denominados plantaciones dendroenergéticos, tienen por objetivo maximizar la acumulación de biomasa aérea al menor costo y tiempo posible. El rendimiento potencial de biomasa depende de la adecuada selección de la especie, el diseño del cultivo (densidad y rotación), regímenes de manejo (niveles de fertilización o riego); y principalmente de factores no manipulables del sitio como el clima, la fertilidad de los suelos, la incidencia de agentes bióticos de daño, entre otros (*Oliveira et al.*, 2015). Entonces, el mayor potencial para la producción de bioenergía es a través del uso de especies de alto rendimiento, pertenecientes a los géneros *Eucalyptus* , *Populus*, *Salix* y Acacia (*King et al.*, 2013; *Eufrade et al.*, 2016; *Esquivel et al.*, 2013; *Sandoval*, 2011; *Sandoval et al.*, 2012, 2015; *Rodriguez*, 2016; *Navarro et al.*, 2016).

Gran incerteza existe respecto a la potencialidad productiva de estas plantaciones dado el amplio rango de productividades reportado en la literatura y la carencia de una herramienta que permita estimar niveles de productividad para distintas especies en condiciones de sitio variables (*Hart et al.*, 2015). El uso de modelos basados en procesos (MBP) es sugerido (*Almeida et al.*, 2004) cuando sólo es posible disponer de información edafoclimática. El modelo 3-PG (Physiological Principles Predicting Growth) ha sido parametrizado en especies con fines madereros de rápido crecimiento y manejos silvícolas tradicionales (*Landsberg and Sands*, 2011; *Landsberg and Waring*, 1997). Sin embargo, escasos estudios existen para plantaciones dendroenergéticos del género *Populus* y *Salix* (*Amichev et al.*, 2011, 2010, 2012; *Hart et al.*, 2015; *Headlee et al.*, 2013; *Prilepova et al.*, 2014; *Zalesny et al.*, 2012) y aún menos para *Eucalyptus* (*González et al.*, 2016). Dado el bajo nivel de información disponible para el estado actual del clima, es aún más desconocido los potenciales efectos del cambio climático sobre el

potencial productivo de plantaciones dendroenergéticos.
Escenarios de cambio climáticos acompañados de MBP resultan útiles para la determinación de potenciales riesgos productivos en plantaciones dendroenergéticos (*Almeida et al.*, 2009). Debido a la alta demanda de recursos que este tipo de plantaciones requiere en términos de consumo de agua y nutrientes para la producción de biomasa (*Albaugh et al.*, 2017) es posible plantear que modificaciones en los patrones climáticos provoquen una modificaciones inesperadas en la acumulación de biomasa aérea en plantaciones forestales con fines energéticos. Así, en el presente estudio se planteó la siguiente hipótesis general: La acumulación de biomasa aérea en plantaciones dendroenergéticos de *Eucalyptus globulus* se incrementara producto del aumento en los niveles de CO_2, temperatura y reducción en las precipitaciones provocadas por el cambio climático, este incremento no se diferenciara entre los niveles de densidad de plantación y condiciones de sitio.

Objetivo General

Determinar la acumulación de biomasa aérea de plantaciones dendroenergéticos de *Eucalyptus globulus* mediante un modelo basado en procesos (3-PG) y evaluar el impacto del aumento en los niveles de CO_2, temperatura y reducción en las precipitaciones provocadas por el cambio climático.

Objetivos Específicos

- Evaluar la capacidad del modelo 3-PG de predecir la productividad de biomasa aérea de plantaciones dendroenergéticos de *E. globulus* establecidos en dos sitios, condiciones de manejo y niveles de densidad contrastantes.

- Determinar el impacto del aumento en los niveles de CO_2, temperatura y reducción en las precipitaciones provocadas por el cambio climático sobre la acumulación de biomasa aérea futura de plantaciones dendroenergéticos de *E. globulus*.

CAPITULO I

A process-based model to evaluate aboveground biomass for *Eucalyptus globulus* Labill short-rotation bioenergy plantings

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ABSTRACT

Uncertainty of biomass estimates from short-rotation bioenergy plantings have challenged industrial bioenergy production projects in many parts of the world. The 3-PG process based model was evaluated on its capability to predict aboveground biomass of *E. globulus* energy crops established at 5000, 10000 and 15000 trees ha^{-1}. Two sites were selected to determine the potential yield of these crops. The first site of low yield (volcanic sands) was established with intensive management (site preparation, fertilization, fertirrigation in summer and weed control until crown closure); and the second site of high natural productivity (volcanic ash) with less intensive management (soil preparation, weed control and initial fertilization), and the model was parameterized with information from this sites. Parameters of this type do not exist for this species cultivated for purposes of energy production in South America and even less for Chile. The 3-PG model was efficient in the determination of above ground biomass of short rotation crops cultures (RMSE ranged 2.6-6.5 Mg ha^{-1}). Our results suggest that initial stocking does not affect aboveground biomass accumulation for a 4 year rotation. However, mean individual tree diameter and proportion of foliage biomass at harvesting were affected by site and initial stocking. The application of this tool to the analysis of the productive potential of the soil in the center of Chile, combined to the estimated accumulated biomass levels between 83 and 115 Mg ha^{-1}, suggests that this type of crop could be attractive for farmers and forestry companies and electric.

Keywords: Aboveground biomass; 3-PG model; *Eucalyptus globulus*; Short-rotation; Bioenergy plantings; Dendroenergetic.

Article submitted for journal publication: *Biomass and Bioenergy*

INTRODUCTION

The world has experienced a steady increase in energy demand that is primarily met by fossil fuels (*IPCC*, 2007; *Carroll and Somerville*, 2009). The environmental externalities of energy production based on fossil fuels, added to the uncertainty of its future supply and the constant increase in the cost of extraction and transformation, place renewable energy from biomass within a sustainable alternative energy production (*Goldemberg and Coelho*, 2004; *King et al.*, 2013). Future policies will require, in the medium and long term, the use of renewable raw materials to produce energy or liquid fuels; establishing production and efficiency standards along with incentives for the establishment of crops for energy purposes represent (*Giampietro et al.*, 1997; *Sissine*, 2007; *CONAF*, 2015). In general, agricultural crops have been widely used as feedstock for energy production (*Demirbas*, 2009). However, 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 (*Tilman et al.*, 2006; *Semere and Slater*, 2007; *Esquivel et al.*, 2013).

Under this scenario, forestry crops for energy purposes or also called dendroenergetic crops, aim to maximize the accumulation of aerial biomass at the shortest time and minimum cost. Biomass yield potential depends on several factors such as: suitable selection of species, crop design (initial planting density and rotation), management regimes (weed control, fertilization, irrigation); and climatic conditions. In addition, incidence of biotic agents may damage and reduce levels of productivity (*Oliveira et al.*, 2015). Largest potential for bioenergy production has emphasized the use of species plasticity and high yield of the Eucalyptus genus, Populus and Salix (*King et al.*, 2013; *Eufrade et al.*, 2016) . In the case of Eucalyptus sp., being one of the most widely planted species, great uncertainty exists regarding their potential for bioenergy production given the wide range of productivities reported in the literature and the lack of models that may be used broadly to estimate site specific productivity for different environments and silvicultural treatments (*Hart et al.*, 2015). The use of process-based models is suggested when only soil and climatic information is available (*Almeida et al.*, 2004). The 3-PG model (Physiological Principles Predicting Growth) has been extensively parameterized for fast-growing species under traditional (low initial planting density, not coppiced) silvicultural management of plantations (*Landsberg and Waring*, 1997; *Landsberg and Sands*, 2011). However, there are scarce number of studies using process based models to estimate productivity of dendroenergetic crops. Most studies have focused on Populus and Salix species (*Amichev et al.*, 2010, 2011, 2012; *Zalesny et al.*, 2012; *Headlee et al.*, 2013; *Prilepova et al.*, 2014; *Hart et al.*, 2015) but few have considered Eucalyptus sp. (*González et al.*, 2016).

In the south central zone of Chile, there is a highly degraded area in hands of rural landowners who could potentially be destined to dendroenergetic plantations and depending of edaphoclimatic conditions could be an economically feasible alternative for forestry investors or energy companies (*CONAF*, 2015). The productivity levels associated with *E. globulus* dendroenergetic crops are unknown and traditional *E. globulus* crops are destined to meet a demand for fibre. The use of wood energy crops will open a new niche market for bioenergy production in forestry, agronomic and electric companies. Thus, the objective of this study is to validate the 3-PG model to predict productivity in *E. globulus* wood energy crops and to use this model in in two contrasting productivity sites that allow exploring different management strategies such as the rotation period among others that facilitate the decision-making by farmers and entrepreneurs.

METHODOLOGY

Sites description

Two experimental *E. globulus* short rotation energy plantations established in contrasting sites of Central South Chile. The sites considered a high fertility without irrigation (HFni) and a low fertility irrigated (LFir) site. The HFni site was located near Collipulli in the foothills of Andes mountains at an elevation of 580 m asl (Fig. 1) with 1899 mm annual rainfall and mean temperatures of 15.9 °C during summer and 7.2°C during winter (1995 – 2015 period). Soils are deep and derived from recent volcanic ash (trumao) classified as medium mesic Typic Haploxerand (Andisols) (*Martínez*, 2004; *Staff*, 2006). Previous land use was a 22 year old Pinus radiata D. Don. plantation harvested in 2009. In January 2010, harvesting residues were removed mechanically. A pre-plant broadcast vegetation control treatment was applied using 3.0 kg ha^{-1} glyphosate. Seedlings were shovel planted in March 2010. Trees were fertilized at planting with nitrogen, phosphorus and boron at 30, 20, and 3 g elemental plant^{-1}, respectively, applied 20 cm from the planting hole on the soil surface. Additional vegetation control was completed in December 2010, April 2011 and September 2011 using 2.0 kg ha^{-1} of glyphosate each time. Protective screens were used to avoid herbicide drift onto the plants. The LFir site was located near Yumbel in the central valley of Chile at an elevation of 120 m asl (Fig. 1). Mean annual rainfall was 990 mm with mean summer temperature of 17.4 °C and 8.5 °C during winter (period 1995-2015). Soils consisted of deep volcanic sand (arenales) classified as mixed thermic Dystric Xeropsamment (Entisols) (*Martínez*, 2004; *Staff*, 2006). Previous land use at this site was a *Pinus radiata* D. Don hedge field under fertigation. In 2011, soils were ploughed at 30 cm and pre and post planting weed controls were applied until canopy closure. In 2012, all trees were cut to produce sprouts during the second year after establishment. Fungicide was applied to sprouts and weed control was applied until canopy closure. To reduce summer water stress and nutrient demand at the LFir, fertigation was applied between October and May of each year supplying 650 mm of water. Nutritional addition in the water stream considered NPK, Ca, Mg, S, Fe, Zn, Cu and B during the three years of trial evaluation.

Experimental design, stand measurements and biomass sampling

The study consisted of a factorial design arranged in completely randomized blocks with three replicates. Treatments at each site considered initial planting density at three stocking

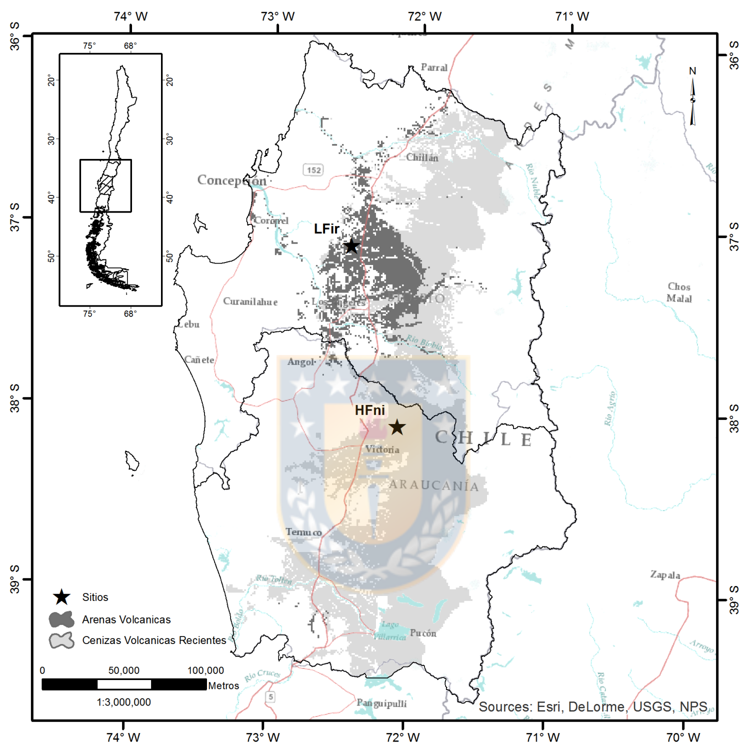

Figure 3.1: Location of sites planted with *E. globulus* growing as short rotation energy crops in south Chile. Sites were established at initial densities 5000 vs 15000 trees ha^{-1} in high soil fertility without irrigation (HFni) and 5000 vs 10000 trees ha^{-1} in low soil fertility with irrigation (LFir).(source: Own development).

levels of 5000 (5k) and 15000 (15k) trees ha^{-1} at the HFni and 5000 (5k) and 10000 (10k) trees ha^{-1} at the LFir. Experimental units at the HFni were square plots of 644.1 m^2 for 5k and 590.5 m^2 for 15k initial planting densities. At the LFir site each experimental unit was a square plot of 140 m^2 for 5k and of 69 m^2 for 10k initial planting density. Measurement plots considered 25 trees at the LFir and 30 trees at HFni. Since February of 2015, annual individual tree height m (H), diameter at the height of 0.1 m (root collar diameter, RCD) and diameter at the 1.3 m height (D) was measured in all live trees of the central plot. During the summer of 2015 and 2016 a destructive biomass sampling was carried out by extracting three trees from the buffer zone of each treatment plot. Harvested trees were selected to cover the range in height and diameter found with the tree measurements. We chose trees that were undamaged with a full set of neighbours (living trees in the eight adjacent planting spots) when possible. Selected trees were measured for H, RCD and D, and cut at the ground line. Twenty leaves were selected from throughout the crown for the specific leaf area determination. All branches were cut from the stem. Foliage and branch material were separated in the field (for small trees) or after drying (to facilitate separation for the small Acacia leaves). Ten centimeter long discs were cut from the stem at the base, at 1.3 m up the stem and half way between the top of the tree and the base of the live crown. Fresh weight of the stem discs and the remaining stem sections were recorded in the field. The remaining stem sections were left in the field and their dry weight was estimated from the dry weight to fresh weight ratios of the stem discs. All samples were dried at 65°C to a constant weight. Linear regression models were used to estimate biomass by component (foliage, branches and stem) and were applied for growth data. In addition, significant differences between levels of density for each age were evaluated through analysis of variance for the variables: Aboveground, stem, foliage biomass and average diameter.

Models of biomass per component

A general linear model was used to estimate individual tree biomass equations for foliage, branches and stem at individual tree level (*Albaugh et al.*, 2017). Dependent variables considerer foliage, branches and stem individual tree biomass, and the independent variables were site, initial stocking and individual tree dimensions measured in each tree (H, RCD and D). The general form was:

$$w = x\, s_i\, s_t \tag{1.1}$$

Where was the biomass of each component (foliage, branches and stem), x was D^2H and $(RCD)^2H$ from the dimensional measurement, s_i was the site and s_t was the initial stocking. All interactions were included in the full model. Variables s_i and s_t were incorporated as categorical variables. Models were compared D^2H and $(RCD)^2H$ models and selected the model with the highest R^2 . If heteroscedasticity was evident in the residuals, we used a natural logarithmic transformation. Model selection considered that no significant variables (p-value $<$ 0.05) were removed from the model. If heteroscedasticity was evident in the

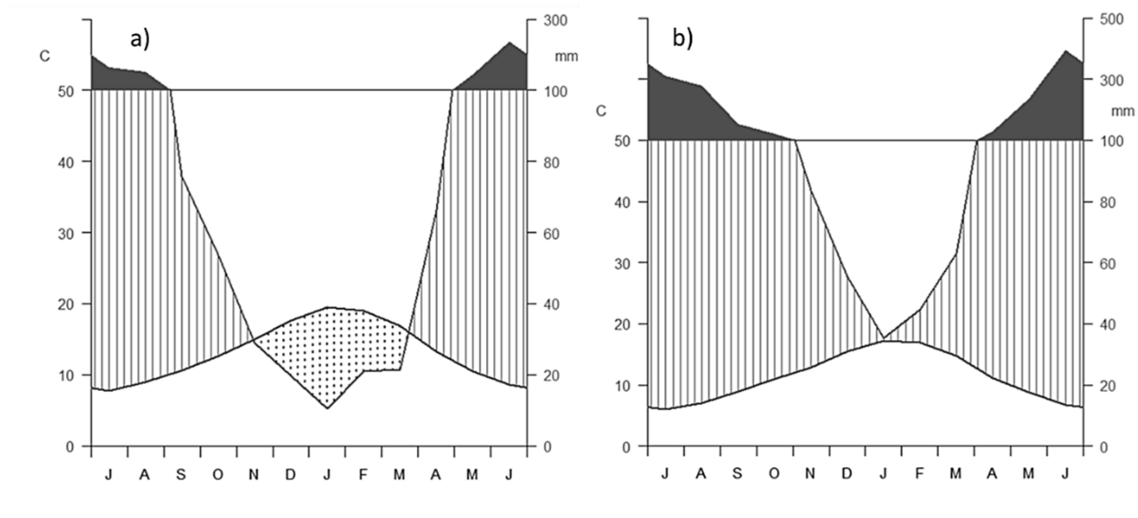

Figure 3.2: Climatic diagram characteristics of sites planted with *Eucalyptus globulus* growing as short rotation energy crops in south Chile, Note: a) lower fertility with irrigation site and b) higher fertility without irrigation site. Right axis corresponds to the monthly average of rainfall and left axis to the daily average temperature, dots surface area corresponds to drought period, stripes surface area corresponds to the period with precipitation, and filled surface area correspond to surplus of precipitation. The information corresponds to the monthly average between 1995 and 2016 (Source: `http://dgasatel.mop.cl/`).

residuals, natural logarithmic transformation was used to transform the data (*Baskerville*, 1972).

Meteorological information

Historical information was obtained from local meteorological stations (Source: Meteorological Direction of Chile `http://dgasatel.mop.ml/`). The model 3-PG requires climatic information at a monthly level from in-situ meteorological stations established at each site from 2015 to 2016. Recorded data consisted of monthly information of maximum and minimum temperature (°C) and rainfall (mm). Vapour pressure deficit (VDP) and Monthly average daily solar radiation (Q, MJ m^{-2} day^{-1}) was calculated from meteorology data (*Bristow and Campbell*, 1984).

3-PG model parameterization

Specific adjusted parameters in this study was: (i) Constant and power of the biomass ratio of stem vs diameter (α_s and n_s) and the ratio between foliage and stem biomass for diameters of 2 and 20 cm (α_f and n_f); (ii) mortality range of a rotation ($gammaNx$), seedling mortality rate ($gammaN0$), age at which mortality rate has mean value ($tgammaN$), shape of mortality response ($ngammaN$), Maximum stem mass per tree for a stocking of 1000 trees ha^{-1}, power in the self-thinning rule ($thinPower$); (iii) specific leaf area at the age = 0

(SLA0), in mature trees (SLA1) and age at which $SLA = (SLA0 + SLA1)/2$ and (iv) ratio between bark biomass and branches at age = 0 (fracBB0), in mature trees (fracBB1) and age at which $fracBB = (fracBB0 + fracBB1)/2$ and minimum basic density for young trees (rhoMin), maximum basic density for older trees (rhoMax) and $rho = (rhoMin + rhoMax)/2$.

Allometric and age dependent parameters

A nonlinear model considering stem (w_s), foliage (w_f) and the ratio between foliage vs stem biomass (p_{fs}) was fitted, the functional form of model was:

$$y = aD^n \tag{1.2}$$

Where y was the independent term (w_s,w_f and p_{fs}), a and n were estimated parameters (a was a scale parameter and n a constant of proportionality between y vs D). The effect of site and initial stocking on allometric parameters was evaluated by incorporating these variables as categorical (*Schabenberger and Pierce*, 2001).
A Gaussian-type model was used to fit the relationships for specific leaf area (m^2 k^{g-1}), mortality (% dead trees year^{-1}), ratio between bark biomass and branches and basic density (Mg m^{-3}) (*Landsberg and Waring*, 1997). The structure of the model was:

$$y = y_1 + (y_0 - y_1)\exp(-\ln(2)(t/t_y)^n) \tag{1.3}$$

Where y was the variable over time t (years), y_1 was the lower limit of the function, y_0 was the upper limit, t_y was to age when $y = (y_1 + y_0)/2$ and n was a shape parameter. The adjustments were made by the nlin procedure in SAS 9.4 software by minimizing the sum of squares of the error following the Gauss-Newton convergence criterion.

Model performance evaluation

Evaluation of the model was performed using a linear regression between the observed and estimated values (*Almeida et al.*, 2004). Selected variables for evaluation of the model were average diameter (D), stem biomass (w_s), foliage biomass (w_f) and aboveground biomass (w_{AGB}). We obtained information from experiments not used in the parameterization of the model (see figure 3.1), *E. globulus* planted different density levels (5000, 7500, 10000 and 15000 trees ha^{-1}) and site conditions (volcanic sands and clays). With this data was determined coefficients and statistics obtained were used to evaluate the predictive capacity of the 3-PG model. An efficiency index that ranges from -1 (poor fit) to 1 (perfect fit) was calculated (EI) to test the accuracy of the model. Finally, the root mean square error (RMSE) was calculated to provide an estimate of precision using the same units of the dependent variable.

RESULT

Model 3-PG Parameterization

It consisted in two phases: Determination of the biomass equations and parameter definition of the 3-PG model. To determine the biomass per component in the growth data, regression equations were constructed. Stocking significantly influenced the foliage and stem biomass regressions and site significantly influenced the branch regressions (4.1). Values of the calibrated growth parameters for the two sites and two stocking were present in table 3. Allometric characteristics of trees established in sites with higher natural fertility and no irrigation (HFni) differed significantly from those trees established in sites with lower natural fertility but with irrigation in summer periods (LFir). The parameter a_s was 27% higher at HFni (0.0598) compared to LFir (0.044). Differences of less than 1% were observed for the n_s parameter among the evaluated sites (mean value 2.66). Highest level stocking effect was significant for n_s (2.77 in 5k vs 2.54 in 10k), p_{fs2} (0.46 in 5k vs 0.47 in 10k) and p_{fs20} (0.038 in 5k vs 0.039 in 10k) parameters at the lowest fertility site. Concerning the canopy structure and processes parameters, SLA (specific leaf area) at the beginning simulation (SLA0) and at leaf maturity (SLA1) ranged from 8.96 (SLA0) to 2.86 m2 kg-1 (SLA1). Mortality observed an initial of the period was 8% (gammaNo=0.92) and rate of whole growth period of 41% (gammaNx=0.59). Maximum stem mass per tree (wSx1000) at the lowest stocking level parameter was 367 (HFni) and 350 (LFni) vs the highest stocking level was 480 (HFni) and 440 (LFni) and power in selft-thining (thinPower) at the lowest stocking level was 2.33 (HFni) and 2.05 (LFni) vs the highest stocking level was 1.93 (HFni) and 1.68 (LFni). Other parameters of the conversion factors were summarized in table 4.3.

Table 4.1: Independent variables and estimated regression coefficients used in estimating biomass by component (foliage, branch and stem) of *E. globulus* growing as short rotation energy crops in south Chile. Sites HFni and LFir were planted at stocking densities of 5000 vs 15000 tress ha^{-1} in HFni and 5000 vs 10000 tress ha^{-1} at LFir

Site	**Init. Stocking**	**Ind. variable**	b_0	b_1	**MSE**
Foliage mass					
HFni	5k	d2hlog	-3.42709	0.62073	0.7372
	15k	d2hlog	-3.98397	0.62073	0.7372
LFir	5k	d2hlog	-3.42709	0.62073	0.7372
	10k	d2hlog	-3.98397	0.62073	0.7372
Branch mass					
HFni	5k	d2hlog	-7.01665	1.16009	0.86224
	15k	d2hlog	-7.01665	1.16009	0.86224
LFir	5k	d2hlog	-4.59757	0.76875	0.86224
	10k	d2hlog	-4.59757	0.76875	0.86224
Stem mass					
HFni	5k	d2hlog	-1.6831	0.6455	0.8515
	15k	d2hlog	-3.45049	0.92022	0.8515
LFir	5k	d2hlog	-1.6831	0.6455	0.8515
	10k	d2hlog	-3.45049	0.92022	0.8515

where, HFni = high soil fertility without irrigation and LFir = low soil fertility with irrigation, *d2hlog* was the natural logarithm of the diameter at breast height (D) squared times height (H), D and H was expressed in cm, b0 and b1 were the estimated coefficients, intercept and slope respectively, MSE is the mean square error of the regression, output is at the individual tree scale in kg for each component, equation form:

$$DV = \exp(b_0 IV + b_1) \times \exp(MSE/2) \tag{1.4}$$

DV and IV were the dependent variable and independent respectively. Same b_0 and b_1 for site and initial stocking combination implies that site or initial stocking does not significantly affect the relationship.

Table 4.2: Average measurement for diameter breast height, foliage, stem, aboveground biomass and yield of *E. globulus* growing as short rotation energy crops in south Chile. Two stocking levels were considered: 5k vs 10k in LFir and 5k vs 15k in HFni. Pv is the p-value for the statistical significance of the initial stocking effect. Bolt values indicate p-values less than 0.05.

Site/Age	**Diameter breast height(cm)**			**Foliage Biomass (Mg ha^{-1})**			**Stem Biomass (Mg ha^{-1})**			**Aboveground biomass (Mg ha^{-1})**			**Yield (Mg ha^{-1} year^{-1})**		
HFni	**5k**	**15k**	**Pv**	**5k**	**15k**	**Pv**	**5k**	**15k**	**Pv**	**5k**	**15k**	**Pv**	**5k**	**15k**	**Pv**
4.58	7.5	5.8	**0.006**	4.5	8.3	**0.022**	48.9	75.0	0.1683	53.4	83.3	0.145	18.2	11.7	0.145
4.75	7.7	5.7	**0.002**	5.0	8.5	**0.031**	56.1	77.1	0.2655	61.0	85.6	0.229	18.0	12.9	0.229
5.08	7.9	6.0	**0.005**	5.4	9.0	**0.035**	65.9	85.5	0.3444	71.3	94.5	0.299	18.6	14.0	0.299
5.25	8.0	6.1	**0.005**	5.7	9.5	**0.034**	71.3	93.1	0.3366	77.0	102.6	0.293	19.5	14.7	0.293
5.58	8.1	6.2	**0.005**	5.9	10.0	**0.033**	76.3	102.8	0.3067	82.2	112.7	0.269	20.2	14.7	0.269
5.75	8.1	6.2	**0.005**	6.0	10.1	**0.031**	78.3	105.6	0.2967	84.3	115.8	0.260	20.1	14.7	0.260
LFir	**5k**	**10k**	**Pv**	**5k**	**10k**	**Pv**	**5k**	**10k**	**Pv**	**5k**	**10k**	**Pv**	**5k**	**10k**	**Pv**
2.58	6.8	5.3	**0.014**	4.4	5.1	0.371	20.5	20.7	0.9414	24.8	25.7	0.791	10.0	9.60	0.791
2.83	7.4	5.6	**0.013**	5.3	6.2	0.374	28.8	28.8	0.9944	34.1	35.0	0.850	12.4	12.1	0.850
3.08	8.4	6.4	**0.015**	6.7	7.8	0.380	44.6	44.5	0.9947	51.3	52.3	0.883	17.0	16.6	0.883
3.33	9.2	7.0	**0.018**	7.7	9.0	0.378	57.9	58.0	0.9875	65.6	67.0	0.879	20.1	19.7	0.879
3.58	9.7	7.4	**0.020**	8.4	9.8	0.382	67.7	67.8	0.9890	76.1	77.6	0.888	21.7	21.2	0.888
3.83	9.9	7.5	**0.020**	8.7	10.2	0.385	72.9	72.9	0.9961	81.6	83.1	0.897	21.7	21.3	0.897

Table 4.3: Functional form and parameters are different from those given by Sands and Landsberg (2002) fitted for HFni and LFir and initial densities 5k, 10k and 15k

Meaning/comments	Name	Units	HFni		LFir	
Allometric relationships & partitioning			**5k**	**15k**	**5k**	**10k**
Foliage: stem partitioning ratio @ D=2 cm	pFS2	-	0.4320	0.4431	0.4681	0.4793
Foliage: stem partitioning ratio @ D=20 cm	pFS20	-	0.0354	0.0363	0.0384	0.0393
Constant in the stem mass vs. diam. Relationship	aS	-	0.0598	0.0598	0.0329	0.0550
Power in the stem mass vs. diam. Relationship	nS	-	2.6769	2.6769	2.7734	2.5383
Stem mortality & self-thinning						
Mortality rate for large t	gammaNx	%/year	0.59	0.59	0.59	0.59
Seedling mortality rate (t = 0)	gammaN0	%/year	0.92	0.92	0.92	0.92
Age at which mortality rate has median value	tgammaN	years	1.82	1.82	1.82	1.82
Shape of mortality response	ngammaN	-	2.00	2.00	2.00	2.00
Max. stem mass per tree @1000 trees/hectare	wSx1000	kg/tree	367	480	350	440
Power in self-thinning rule	thinPower	-	2.05	1.68	2.33	1.93
Specific leaf area						
Specific leaf area at age 0	SLA0	m2/kg	8.96	8.96	8.96	8.96
Specific leaf area for mature leaves	SLA1	m2/kg	2.86	2.86	2.86	2.86
Age at which specific leaf area = (SLA0+SLA1)/2	tSLA	years	3.53	3.53	3.53	3.53
Branch and bark fraction (fracBB)						
Branch and bark fraction at age 0	fracBB0	-	0.99	0.99	0.99	0.99
Branch and bark fraction for mature stands	fracBB1	-	0.45	0.45	0.45	0.45
Age at which fracBB = (fracBB0+fracBB1)/2	tBB	years	2.27	2.27	2.27	2.27
Basic Density						
Minimum basic density - for young trees	rhoMin	t/m3	0.535	0.535	0.535	0.535
Maximum basic density - for older trees	rhoMax	t/m3	0.560	0.560	0.560	0.560
Age at which rho = (rhoMin+rhoMax)/2	tRho	years	4.061	4.061	4.061	4.061

Model 3-PG performance

Calibrated parameters (4.3) were used for simulating the growth at each site and stocking condition. 3-PG model predicted with high efficiency the stand mean diameter at low fertility site (efficiency index of 0.93 for 5k and 0.89 for 10k) and in lowest stocking level (5k) at the high fertility site (0.83), however, the estimation efficiency was poor in the highest stocking level (0.41). The tests applied to regression coefficients between the 3-PG model estimates and the observed stand mean diameter values showed that at site of high fertility and 15k stocking level, the intercept was significantly different from 0 and slope significantly different from 1. Prediction of foliage biomass was efficient at the low fertility site (efficiency index of 0.96 for 5k and 0.93 for 10k) and the prediction was poor at the high fertility site (efficiency index of 0.67 for 5k and -0.12 for 15k). Efficiency index results coincided with the tests applied to regression coefficients between the foliage biomass observations and the predictions of the 3-PG model where at site of high fertility and 15k stocking level, the intercept was significantly different from 0 and slope significantly different from 1. Stem biomass represented more than 80 % of the above ground biomass, therefore 3-PG model performance in prediction of stem and aboveground biomass was the same. Prediction of stem and aboveground biomass was efficient at the low fertility site (efficiency index of 0.945 for 5k and 0.99 for 10k) and at the high fertility site (efficiency index of 0.88 for 5k and 0.945 for 15k). Efficiency index results coincided with the tests applied to regression coefficients between the foliage biomass observations and the predictions of the 3-PG model where at site of high fertility and 15k stocking level, the intercept was significantly different from 0 and slope significantly different from 1.

Model 3-PG Application

Average of the three blocks were used to summarize the growth data and significant differences were tested between levels of initial stocking. Lower stoking effect was significant for stand mean diameter by 2.2 cm (24%) at the two experimental sites in all measurement instances. Highest level stocking effect was significant for foliage biomass by 3.8 Mg ha^{-1} (70%) at the high fertility not irrigate site (HFni) and not significant at the low fertility irrigate site. Stocking effect was not significant for stem, aboveground and yield biomass at two experimental sites for all measurement instances (4.2). Due to differences in age between sites experienced were not evaluated site effect. However, biomass accumulation and yield was higher at the LFir site. At the HFni site, the average accumulated biomass in 5 years (82.9 Mg ha^{-1}) coincides with the accumulated biomass at 3 years at the LFir site (82.4 Mg ha^{-1}).

DISCUSSION

Model 3-PG Parameterization

The results of this study indicated that it is possible to determine a set of parameters using the 3-PG model, allowing the estimation of the detailed growth patterns of time series in stands of forest plantations. Values of parameters are consistent with those of other studies they are generic enough that allows their use as a practical tool in the prediction of biomass and provides important information for making forest management decisions. The most important parameters of the model, such as the maximum canopy quantum efficiency (α_{cx}) take values that can be applied universally and are adopted by default of the original model (*Sands and Landsberg*, 2002; *Landsberg et al.*, 2003) while other parameters are obtained by calibration as was done explicitly in this study. Parameters such as allometrical relationships diameter and stem biomass, diameter and partition of foliage and stem biomass, stress mortality and self-thinning mortality, specific leaf area, basic density and biomass ratio of bark vs branches (table 4.3). This did not lead to significant errors in the exit values of the variables of interest for the estimation of the aboveground biomass.

The parameterization of 3-PG from the observed data of the different components of biomass and growth in *E. globulus* for contrasting productivity sites was a step-by-step process since the objective was to establish parametric values that would provide good results for all available observations on biomass of stems, branches and foliage (*Sands and Landsberg*, 2002).

Model 3-PG performance

The prediction of characteristics of stand, performed for model 3-PG, is directly related to the estimation of net primary productivity, allometric parameters of stem and foliage biomass, and maximum stem mass per tree (wSx1000) determined for each site and stocking condition. Therefore, the more accurate the determination of stem and foliage biomass by equations (table 4.1), the accuracy in the determination of stand characteristics by 3-PG model is higher. It was observed that the 3-PG model predicts the *E. globulus* aboveground biomass with a similar certainty to that recorded for *E. nitens* in studies carried out in Spain (*González et al.*, 2016; *Headlee et al.*, 2013), Where the coefficients of determination fluctuate between 0.83 to 0.89, which is close to those presented in this study which fluctuate between 0.61 to 0.97. A poor prediction was obtained in the determination of foliage biomass mainly due to the intrinsic variability of this characteristic and these results were consistent with those obtained in other studies (*Fontes et al.*, 2006; *Landsberg et al.*, 2003). Moreover, the prediction of mean stand diameter was accurate (coefficients of determination between 0.71 and 0.92) it is observed in the scatter plot (Fig. 5.3) where the relationship between observed and predicted values grouped close the diagonal line indicates a high predictive capacity of the 3-PG model. The aboveground biomass yield observed in this study was highest to the reported in literature (9.6 and 21.7 Mg ha^{-1} year^{-1}) depending on the rainfall, irrigation, fertilization and management regimes in contrasting to 7.7 and 19.1 Mg ha^{-1} year^{-1} reported in others studies for *E. Nitens* (*González et al.*, 2016).

Model 3-PG Application

Stocking effect was not significant for aboveground biomass in both sites of high fertility and with a natural limitations site, which allows to recommend the use of lower density is appropriate for reduce operative costs of dendroenergetic crops. A similar conclusion was obtained by (*González et al.*, 2016) with *E. nitens* where the density of 3000 trees ha^{-1} was adequate for northeastern area of Spain. Thus, further studies should be focused their efforts on the determination of an optimal number of trees per unit of area. The accumulation of aboveground biomass was not affected by the initial stocking density, but mean stand diameter was affected, which according to the self-thinning law was directly affected by the density of the stand (*Pretzsch and Biber*, 2005). Thus, since the goal of dendroenergetic crops is the production of aboveground biomass, the individual trees dimensions are not important. For the above, a factor to consider in the parameterization of the 3-PG model will be the obtaining of enough samples to accurately model the self-thinning function that covers the entire development of the stand. The difference observed between aboveground biomass accumulation at the site of high fertility and low fertility at the same age ($\approx$ 4 years) was 5 to 10 Mg ha^{-1} according to the stocking level observed. This difference does not represent a decisive factor in terms of economic investment, but it is necessary to consider that to achieve the accumulation presented in this study, the site of lower fertility will require a higher initial investment of irrigation, site preparation, weed control and fertilization. Therefore, in economic terms, the choice of site is a strategic factor and must be studied before making an investment in crops for energy purposes.

The differences observed in stand mean diameter between stocking levels is related to the relationship of tree individual dimensions vs site occupation, it relation establishes that a higher level of occupation or a greater number of trees ha^{-1} the tree size will be smaller (*Pretzsch and Biber*, 2005). Therefore, in both sites it was possible to observe that stand mean diameter was lower in highest stocking levels by 2.15 cm than in lowest levels. Since these types of plantations were designed for the biomass production, the diameter variable was not a relevant factor in productivity terms. Even thought, the operational performance of a harvesting will be negatively affected by low dimensions of trees, therefore, it is essential to develop a density management diagram that allows to optimally manage the occupation of the site maintaining a diametric level optimum for the harvest.

The accumulation of aboveground biomass between the two levels of density (5k vs 15k at HFni and 50k vs 10k at LFir) was not statistically different, in consequence, it is not recommended to establish energy crops with more than 5000 trees ha^{-1}. In both contrasting sites, in natural fertility and drought periods (Fig. 3.2), the effect of initial stocking was not significant. Therefore is possible to generalize that, for the same species, the accumulation of aboveground is affected only by the resources that provide the site such as water and fertility (*Landsberg and Sands*, 2011). For this study, the water resource was 990 mm of annual

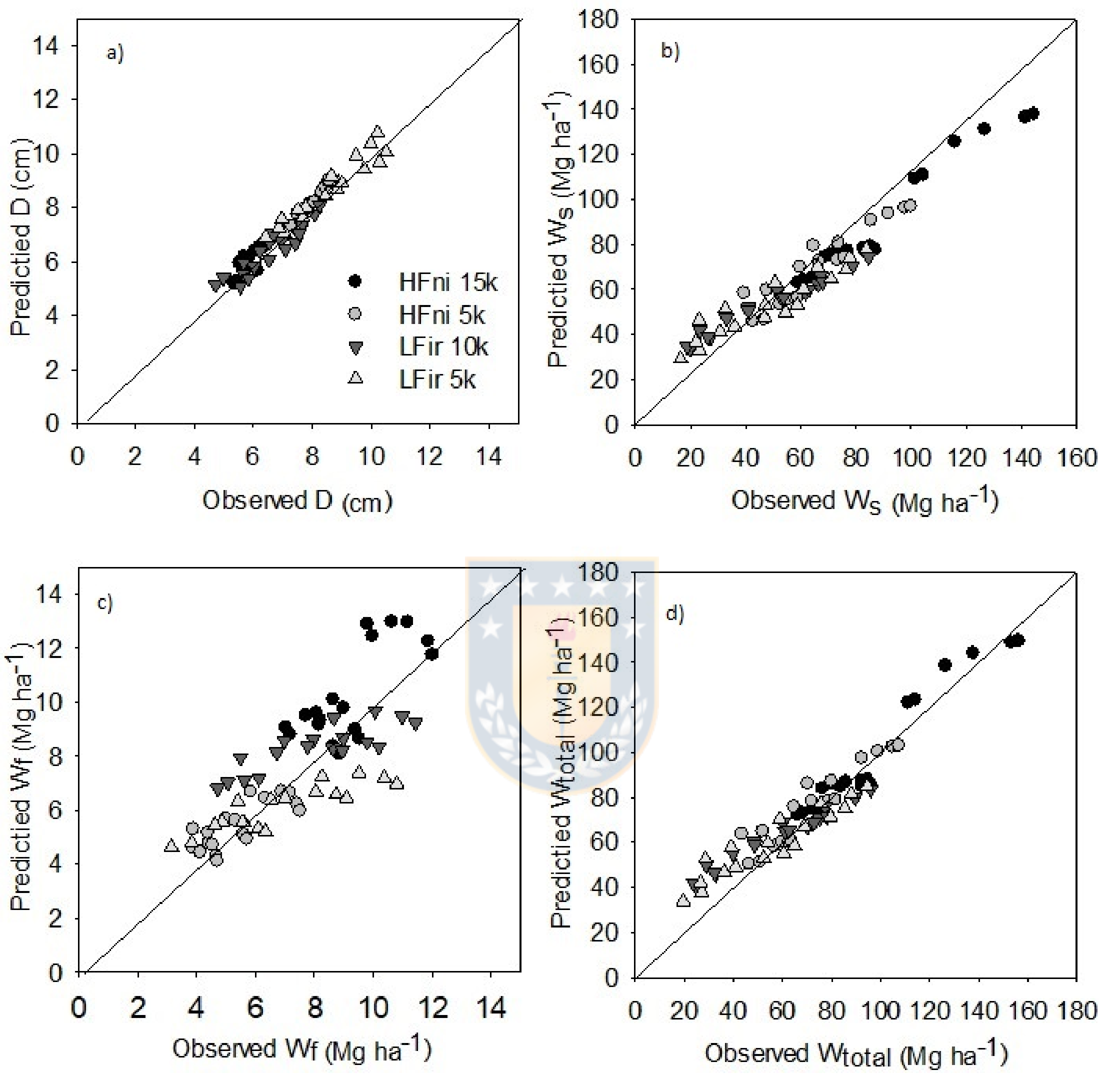

Figure 5.3: Observed and predicted estimates of tree diameter and biomass components by 3-PG model in *Eucalyptus globulus* growing as short rotation energy crops in south Chile. In the figure a) Is the individual tree mean diameter, b) stem biomass, c) foliage biomass and d) aboveground biomass. Site comparisons consider 5000 (5k) vs 15000 (15k) trees ha^{-1} at the high fertility site (HFni, circles) and 5000 vs 10000 trees ha^{-1} at the low fertility site (LFir, triangles). Diagonal line represents a 1:1 ratio.

precipitation + 650 mm of irrigation in summer at LFir vs 1899 mm of annual precipitation at HFni and fertility resource give for type of soil with sand at LFir + fertigation vs clay at HFni. This allows substantially increase the natural productivity of a low fertility site, where the water was contributing in an optimum way in drought periods and along with a supply of nutrients to the site.

The main determinant of productivity for Chilean case is precipitation (*Flores and Allen*, 2004), therefore, in a highly variable territory in terms of rainfall, the use of the 3-PG model as a tool for predicting, planning and evaluating dendroenergetic crops is paramount because of its flexibility, which is not possible through local empirical models. The 3-PG model proved to be a tool with high potential applicability for the aboveground biomass quantification of *E. globulus* dendroenergetic crops. The model allowed an efficient determination of this accumulation along with others stand characteristic such as biomass of foliage, stem and average diameter. In addition, it was concluded that stocking effect was not affect for aboveground biomass accumulation and that an intensive management allows to equalize the productive potential between a site of low fertility and one of high fertility.

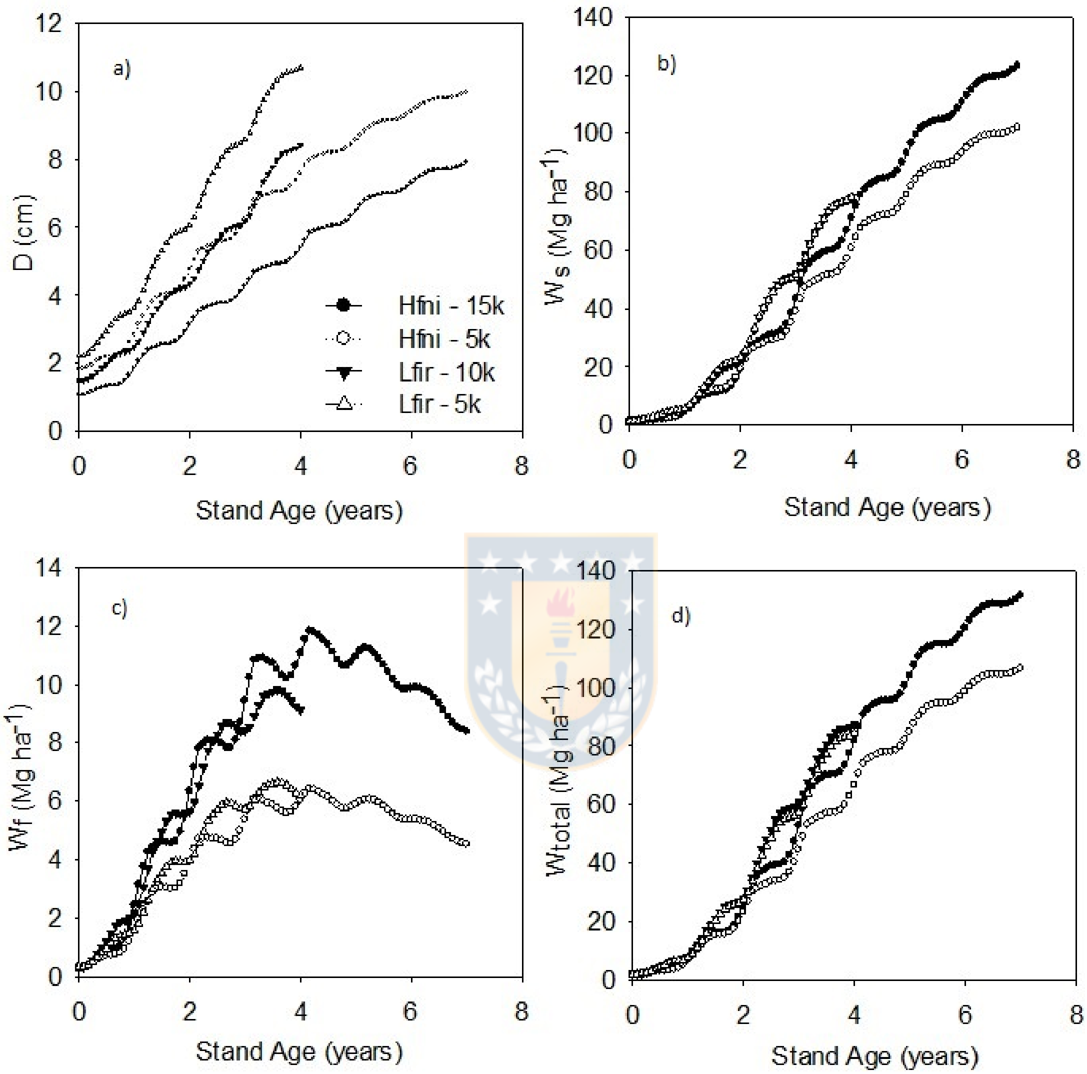

Figure 5.4: Growth comparison estimated by 3-PG model in Eucalyptus globulus growing as short rotation energy crops in south Chile. a) Individual tree mean diameter, b) stem biomass, c) foliage biomass and d) aboveground biomass. Site comparisons consider 5000 (5k) vs 15000 (15k) trees ha^{-1} at the high fertility site (HFni, circles) and 5000 vs 10000 trees ha^{-1} at low fertility site (LFir, triangles)

CAPITULO II

Efectos potenciales del cambio climático sobre el crecimiento de cultivos forestales de corta rotación con fines energéticos en el sur de Chile

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Key words: Global Change, 3-PG model, *Eucalyptus globulus*.

INTRODUCCIÓN

Los dañinos efectos al medio ambiente provocados por el uso de combustibles fósiles y la incertidumbre respecto a la oferta futura de estos, ubican a los cultivos forestales de corta rotación como una fuente sustentable de materia prima para la producción de energía *Demirbas* (2009). La producción eficiente de energía basada en biomasa de cultivos forestales de corta rotación, necesariamente implica una planificación de a corto y mediano plazo, con la finalidad asegurar el abastecimiento de centros de consumo. Para lograr esta planificación, se requiere del uso de herramientas predictivas sensibles a cambios futuros y que determinan el crecimiento de cultivos forestales, con la finalidad ultima de reducir el riesgo futuro de inversiones en energía a base de cultivos forestales con fines energéticos.
La principal fuente de incertidumbre, asociada a cultivos forestales, es el efecto que el cambio climático provocara en las tasas de crecimiento futuras. De esta forma, el aumento observado de la temperatura terrestre producto del efecto invernadero permite posicionar al factor clima como una fuente indiscutible de incertidumbre (*IPCC*, 2007). Así, diversos autores han focalizado sus investigaciones en el estudio de respuestas fisiológicas o cambios en la productividad a condiciones climáticas especificas, entre estas se encuentra la sequía (*Allen et al.*, 2010; *Hanson and Weltzin*, 2000), el aumento en la concentración de CO_2 atmosferico (*Tuhkanen et al.*, 1997; *Jach and Ceulemans*, 1997; *Müller et al.*, 1997; *Graaff et al.*, 2006), el impacto del aumento en CO_2 sobre la productividad (*Hickler et al.*, 2015), modificaciones en la actividad fotosintética como respuesta adaptativa al cambio climático (*Park et al.*, 2019). Siendo pocos los trabajos que se han esforzado por determinar el efecto de sobre el crecimiento y rendimiento de cultivos forestales bajo escenarios de cambio climático como los simulados por el *IPCC* (2007). En esta linea *Almeida, Sands, Bruce, Siggins, Leriche, Battaglia, and Batista* (2009) y *Kirschbaum, Watt, Tait, and Ausseil* (2012) proponen enfoques para cuantificar la variación potencial en términos productivos, mediante modelos regionalizados los cuales permiten detectar zonas de mayor variación.
Por definición, no es posible observar los efectos de modificaciones ambientales en la productividad forestal, ya que solo es posible detectar cambios pasados y diseñar experimentos. Esta experimentación generalmente es limitada cuando se trata de bosques, debido a las grandes escalas espaciales y temporales involucradas, por lo que la utilización de modelos es forma adecuada para analizar y proyectar la productividad forestal bajo condiciones de

cambio climático *Reyer* (2015). Modelos de naturaleza empírica no satisfacen la necesidad de extrapolar estimaciones fuera de su rango de distribución original, de modo que no son útiles cuando el objetivo es proyectar el crecimientos de una masa forestal ante modificaciones climáticas futuras *Landsberg* (2003). Modelos basados en procesos suelen ser la herramienta mas utilizada para proyectar el crecimiento de bosques, a escala de rodal, debido a que incorporan en la determinación de recursos acumulados (e.g. biomasa aerea, volumen, area foliar) variables medioambientales factibles de modificar en condiciones futuras *Fontes et al.* (2010).
El modelo 3-PG (Physiological Principles Predicting Growth) ha sido parametrizado en especies con fines madereros de rápido crecimiento y manejos silvícolas tradicionales (*Landsberg and Sands*, 2011; *Landsberg and Waring*, 1997). Sin embargo, escasos estudios existen para plantaciones dendroenergéticos del género *Populus* y *Salix* (*Amichev et al.*, 2011, 2010, 2012; *Hart et al.*, 2015; *Headlee et al.*, 2013; *Prilepova et al.*, 2014; *Zalesny et al.*, 2012) y aún menos para *Eucalyptus* (*González et al.*, 2016). Dado el bajo nivel de información disponible para el estado actual del clima, es aún más desconocido los potenciales efectos del cambio climático sobre el potencial productivo de plantaciones dendroenergéticos.
Escenarios de cambio climáticos acompañados de MBP resultan útiles para la determinación de potenciales riesgos productivos en plantaciones dendroenergéticos (*Almeida et al.*, 2009). Debido a la alta demanda de recursos que este tipo de plantaciones requiere en términos de consumo de agua y nutrientes para la producción de biomasa (*Albaugh et al.*, 2017) es posible plantear que modificaciones en los patrones climáticos provoquen una modificaciones inesperadas en la acumulación de biomasa aérea en plantaciones forestales con fines energéticos.
De este modo, el presente trabajo tiene por objetivo determinar el impacto del aumento en los niveles de CO_2, temperatura y reducción en las precipitaciones provocadas por el cambio climático sobre la acumulación de biomasa aérea futura de plantaciones dendroenergéticos de *E. globulus*.

METODOLOGÍA

Descripción del Modelo

El modelo utilizado para las proyecciones de crecimiento fue el 3PG, desarrollado por (*Landsberg and Waring*, 1997) el cual fue parametrizado y testeado en el Capitulo 1 del presente trabajo para cultivos forestales de rápido crecimiento con fines energéticos. Este modelo, utiliza una simplificación del uso eficiente de la luz solar y como ésta es utilizada para la determinacion de recursos acumulados en todo el periodo de crecimiento simulado. El modelo determina de forma mensual la productividad primaria neta según la siguiente estructura:

$$NPP = Y \times \alpha_C (1 - \exp(-kL)) Q_0 \tag{2.1}$$

Donde:
NPP = Productividad Primaria Neta ($t\ ha^{-1} mes^{-}1$).
GPP = Productividad Primaria Bruta ($t\ ha^{-1} mes^{-}1$).
Y = Razón entre GPP y NPP (pérdida de GPP por respiración).
K = Coeficiente de extinción de la luz.
L = Indice de Area Foliar.
Q_0 = Radiación solar Incidente (media mensual).
α_C = Modificador ambiental

la determinación de α_C permite implicar cambios climáticos y la evaluación de su efecto sobre el crecimiento. Los modificadores ambientales asociados a escenarios de cambio climático son: modificadores por temperatura, Agua disponible en el suelo (Precipitación y ciclo hídrico) y modificación de crecimiento y conductancia estomática por concentración de CO_2. Las ecuaciones que describen cada uno de estos modificadores se indican a continuación:

$$f_T(T_\alpha) = \left(\frac{T_\alpha - T_{min}}{T_{opt} - T_{min}}\right)\left(\frac{T_{max} - T_\alpha}{T_{max} - T_{opt}}\right)^{\frac{(T_{max} - T_{opt})}{(T_{opt} - T_{min})}} \tag{2.2}$$

$$f_\theta(T_\theta) = \left(\frac{(1 - Asw)/(max_{Asw})}{sw_{const}}\right)^{-sw_{power}} \tag{2.3}$$

$$f_{C\alpha}(C\alpha) = \frac{f_{C\alpha x}(f_{C\alpha})}{350 \times (f_{C\alpha x} - 1) + C\alpha} \tag{2.4}$$

$$f_{Cg}(C\alpha 0) = \frac{f_{Cg0}}{1 + (f_{Cg0} - 1)C\alpha/350} \tag{2.5}$$

Donde:

$$
\begin{aligned}
f_T(T_\alpha) &= \text{Modificador por Temperatura.}\\
f_\theta(T_\theta) &= \text{Modificador por Agua Disponible en el Suelo.}\\
f_{C\alpha}(C\alpha) &= \text{Modificador por Concentracion de } CO_2.\\
f_{Cg}(C\alpha) &= \text{Modificador de conductancia Estomatica por Concentracion de } CO_2.\\
T_\alpha &= \text{Temperatura diaria media mensual.}\\
T_{min} &= \text{Temperatura Mínima de Crecimiento.}\\
T_{opt} &= \text{Temperatura Óptima de Crecimiento.}\\
T_{max} &= \text{Temperatura Máxima de Crecimiento.}\\
Asw &= \text{Agua disponible en suelo actual.}\\
max_{Asw} &= \text{Máxima Agua disponible en el suelo.}\\
sw_{const} &= \text{Déficit hídrico relativo para una reducción del 50 \%.}\\
sw_{power} &= \text{potencia que determina la forma de respuesta del agua en el suelo.}\\
C\alpha &= \text{Concentración de } C0_2.\\
f_{C\alpha x} &= \text{valor de saturación para altos niveles de } C\alpha.\\
f_{C\alpha x} &= f_{C\alpha x700}/(2 \text{ - } f_{C\alpha x700}).\\
f_{Cg0} &= f_{gx700}/(2f_{gx700} \text{ - } 1).
\end{aligned}
$$

En cualquier caso, es necesario contar con información mensual de las variables climáticas que se utilizan en el calculo de biomasa aeréa. Este calculo se deduce de relaciones alométricas determinadas en el Capitulo 1.

Escenarios de cambio climático

Debido a que la actividad antopogénica es la principal causante del cambio climático, el IPCC propuso escenarios de emisiones de gases de efecto invernadero que incorporan variables antropologicas como el crecimiento demográfico, el desarrollo socioeconómico o el cambio tecnológico. En su informe, el *IPCC* (2007) presento cuatro familias (A1, A2, B1 y B2) que exploran vías de desarrollo alternativas incorporando toda una serie de fuerzas tanto demográficas, económicas y tecnológicas, junto con las emisiones de gases de efecto invernadero resultantes. De estos cuatro escenarios, el A1 Estima un crecimiento económico mundial muy rápido, un máximo de la población mundial hacia mediados de siglo, y una rápida introducción de tecnologías nuevas y más eficientes. Se divide en tres grupos, que reflejan tres direcciones alternativas de cambio tecnológico: intensiva en combustibles fósiles (A1FI), energías de origen no fósil (A1T), y equilibrio entre las distintas fuentes (A1B).
Los escenarios propuestos por IPCC fueron simulados mediante modelos de circulación general (siglas en ingles GCM), los cuales corresponden a simulaciones globales que incorpora procesos físicos que ocurren en la atmósfera, criósfera, océanos, biosfera y sus interacciones con los demás componentes del medio ambiente, aplicando las leyes de la termodinámica y mecánica de fluidos. Estos modelos climáticos globales fueron forzados para incorporar los efectos de gases de efecto invernadero y de esta forma lograr predicciones de precipitación, temperatura y otras variables climáticas en periodos futuros.
Debido a su naturaleza global de los GCM y baja resolución espacial, las variables climáticas obtenidas desde un GCM escaladas según características territoriales especificas (vegetación,

topografía e hidrología) produciendo modelos de escala regional (RCM). Para el escalamiento, se han desarrollado dos métodos, el primero corresponde a una aproximación empírica o estadística y el segundo de tipo dinámico, utiliza un modelo físico del sistema a escala regional, produciendo información de alta resolución y una mejor representación de climas extremos. En Chile, el center of climate and resilience research (CR2) proporciona en su plataforma datos obtenidos de una reducción de escala del modelo ECHAM5-A1B mediante una aproximación dinamica llamada PRECIS, sobre una región que incluye Chile, siguiendo un escenario de emisiones A1B con una escala de resolución de 25 km. *Marengo et al.* (2009).
Estos datos fueron utilizados para la generacion de simulaciones de crecimiento bajo condiciones de cambio climático. Los periodos de información analizados fueron el actual (2010-2017), intermedio (2040-2050) y futuro (2075-2085).

Análisis estadístico

Fue evaluada la acumulación de biomasa área de cada componente (Follaje y Fuste) y características dasométricas (Volumen y Biomasa Aérea Total). Fueron considerados los incrementos medios de las variables indicadas anteriormente para comparación estadística entre periodo actual y el futuro. El modelo estadístico aplicado se baso en un diseño factorial

$$y_{ijk} = \mu + \tau_i + \beta_j + \gamma_k + (\tau\beta)_{ij} + (\tau\gamma)_{ik} + (\beta\gamma)_{jk} + (\tau\beta\gamma)_{ijk} + \mu_{ijk} \tag{2.6}$$

Donde:

y_{ijk}	Es la variable en estudio en el i-ésimo Sitio, j-ésima Densidad Inicial y k-ésimo Periodo de simulación.
$\tau_i,\ \beta_j\ y\ \gamma_k$	Son los efectos producidos por cada nivel en estudio.
$(\tau\beta)_{ij},\ (\tau\gamma)_{ik},\ (\beta\gamma)_{jk}\ y\ (\tau\beta\gamma)_{ijk}$	Son los efectos producidos por las interacciones entre cada nivel en estudio.

RESULTADOS Y DISCUSIÓN

El modelo regional utilizado permitió determinar las condiciones climáticas futuras bajo un escenario que plantea un equilibrio entre las distintas fuentes de emisiones de gases de efecto invernadero (AB1), en la figura 3.1 es posible observar la variación presentada para este escenario en términos de precipitación total anual y temperatura media mensual de cada año. Para ambas zonas en estudio es posible determinar un gradiente disminución en la precipitación de 2 % desde el periodo actual al intermedio y de 25 % desde el actual al futuro. Mismo fenómeno es observado en términos de temperatura media, donde el incremento es del orden del 5 % (+0.5°C) desde el periodo actual al intermedio y de un 25 % (+2°C) desde el actual al futuro.

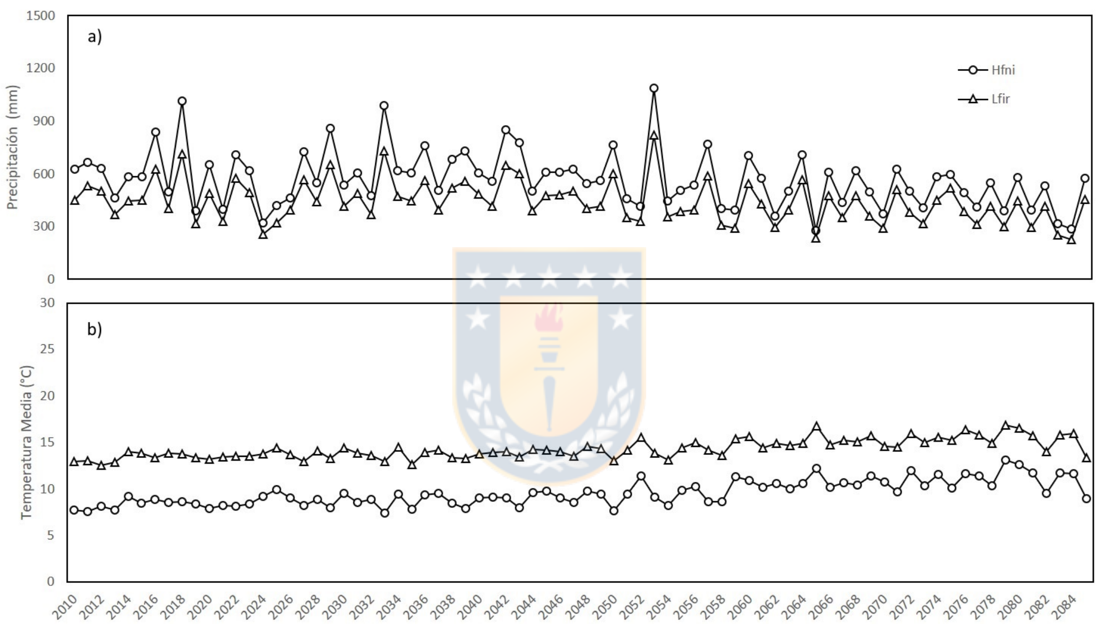

Figura 3.1: Precipitación acumulada anual (mm) a) y Temperatura Media mensual Anual (○C) proyectada por el modelo ECHAM-PRECIS bajo el escenario AB2 para las zonas de estudio (marcadores triangulares para la zona Low Fertility irrigate (Lfir) y circulares para Hight Fertility No Irrigate (Hfir))

Se simulo el crecimiento de cada bloque y se determino la acumulación de biomasa a la edad de 4 años, en este periodo fue realizada la comparación de medias entre los diferentes factores de interés i.e. Biomasa aérea total, biomasa de fuste y follaje y Volumen (cuadro 3.1). De esta comparación se desprende que existen diferencias significativas, para las cuatro variables evaluadas, entre los periodos de simulación. Lo que establece que, bajo condiciones de cambio climático, la disponibilidad de biomasa para la producción de energía sera determinada por las condiciones climáticas futuras.

Cuadro 3.1: P-values para comparación entre los diferentes niveles estudiados (Sitio, Densidad Inicial y Periodo). las Interacciones no resultaron significativas y no se incorporaron en el cuadro

Factor	**Biomasa Aerea (Mg ha^{-1})**	**Biomasa Fuste (Mg ha^{-1})**	**Biomasa Follaje (Mg ha^{-1})**	**Volumen Fustal (m^3 ha^{-1})**
Sitio	1.30e-11 ***	2.38e-12 ***	<2.5-16 ***	2.38e-12 ***
Densidad Inicial	6.58e-10 ***	5.01e-05 ***	<3.8-16 ***	5.01e-05 ***
Periodo Climatico	<2e-16 ***	<2e-16 ***	<4.1-16 ***	<6.2e-16 ***

Se observo un aumento en la tasa de acumulación de biomasa aérea de *E. globulus* en condiciones climáticos futuras. Este aumento, es provocado principalmente por el incremento en la concentración de CO_2 en la atmósfera. Este aumento fue proyectado según las expectativas impuestas por el *IPCC* (2007) las cuales plantean un incremento desde los 350 ppm actuales (periodo de crecimiento de los rodales en estudio 2010 - 2017) a 550 para periodos intermedios (2040-2050) y a 650 ppm para periodos uturo (2075-2085). Este incremento trae consigo modificaciones en las características fisiológicas de especies arbóreas (*Tuhkanen et al.*, 1997; *Jach and Ceulemans*, 1997; *Müller et al.*, 1997; *Graaff et al.*, 2006). Estas modificaciones son posibles de incorporar mediante los modificadores ambientales, pero debido al aumento considerable de biomasa producto del incremento en el CO_2 es necesario revisar o incorporar un nuevo modificador o una alternativa al ya existente (ver figura 3.2).

Esta investigación se limito a la obtención de posibles escenarios de crecimiento de especies con fines energéticos en una distribución espacial limitada. Es necesario destacar la necesidad de abordar una investigación futura desde un punto de vista espacial, donde la parametrización realizada para este tipo de cultivos sea aplicada en un rango de variación climático mas amplio, con la finalidad de detectar potenciales zonas con mayor efecto de condiciones climáticas adversas. Por otro lado, es necesaria la obtención de una mayor cantidad de modelos climáticos de tal forma de obtener predicciones que se logren situar en diferentes condiciones futuras dependiendo de los niveles de precisión de cada modelo climatico y de esta forma verificar los efectos climaticos asociados *Kirschbaum et al.* (2012).

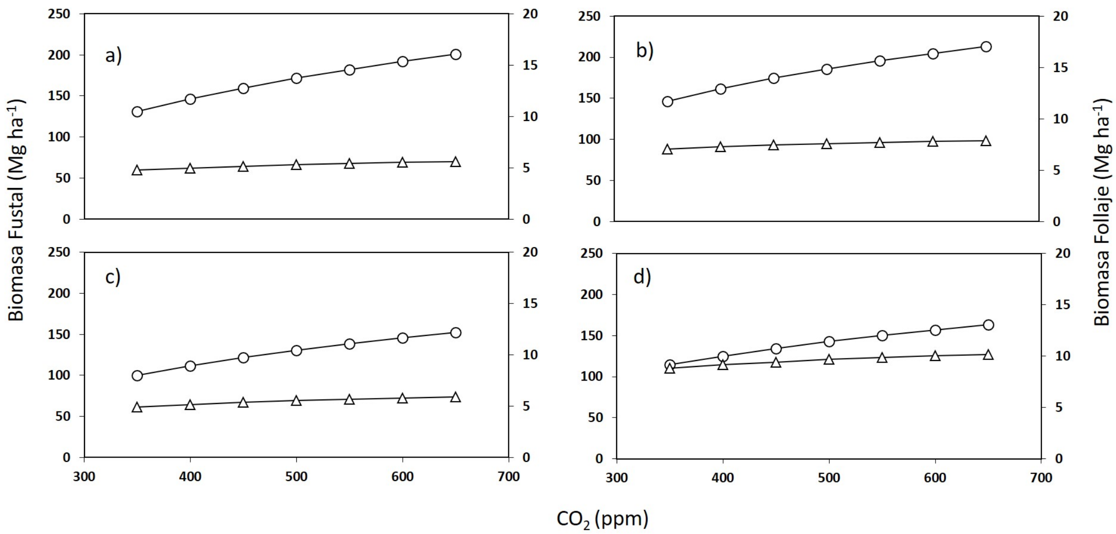

Figura 3.2: Análisis de sensibilidad de la biomasa fustal (marcadores circulares) y de follaje (marcadores triangulares) respecto a variaciones en el CO_2. a) Lfni Baja densidad, b) Lfni Alta densidad, c) Hfir Baja densidad y d) Hfir Alta densidad

CONCLUSIÓN

- Para la zona evaluada, la reducción en precipitación no es suficiente para provocar una reducción en la acumulación de biomasa aérea.
- El aumento en temperatura no genero variaciones debido a que en la zona evaluada esta variable no sobrepaso los limites óptimos para el desarrollo de la especie.
- El incremento en Co_2 atmosférico conduce a un aumento en la acumulación de biomasa aérea total futura en cultivos dendroenergéticos de *Eucalyptus globulus*.

CONCLUSIÓN GENERAL

- El modelo 3-PG demostró ser una herramienta con un alto potencial de aplicabilidad en la cuantificación de la biomasa aérea de los cultivos dendroenergicos de E. globulus. El modelo permitió una determinación eficiente de esta acumulación de biomasa junto con otros indicadores del rodal, como la biomasa de follaje, fuste y el diámetro promedio. Además, se concluyó que la densidad inicial de establecimiento no afectó la acumulación total de biomasa y que un manejo intensivo permite igualar el potencial productivo entre un sitio de baja fertilidad y uno de alta fertilidad.

- Para la zona evaluada, la reducción en precipitación no es suficiente para provocar una reducción en la acumulación de biomasa aérea y de igual forma, el incremento en temperatura no genero variaciones en las tasas de acumulacion de biomasa debido a que en las zonas evaluadas esta variable no sobrepaso los limites óptimos para el desarrollo de la especie.

- El incremento en Co_2 atmosférico conduce a un aumento en la acumulación de biomasa aérea total futura en cultivos dendroenergéticos de *Eucalyptus globulus*, lo que propone que para la zona centro sur de Chile, las condiciones climáticas futuras favorecerán la producción de energía en base a biomasa proveniente de cultivos forestales.

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