ABOVEGROUND BIOMASS GROWTH AND YIELD OF FIRST ROTATION CUTTING CYCLE OF *Acacia* AND *Eucalyptus* SHORT ROTATION DENDROENERGY CROPS[1]

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[1] Received on 30.04.2016 accepted for publication on 20.11.2017.
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ABSTRACT – Chile has strong interest in biomass production for the purpose of generating bioenergy to accomplish environmental standards for clean energy production. However, no yield or productivity information is available about forest crop plantations established at high-initial planting densities dedicated to energy production. The objective of the present study was to provide long-term results of short-rotation forest crops research trials, investigating first cutting cycle most promising species biomass production. Plantations of *Acacia melanoxylon*, *Eucalyptus camaldulensis*, *Eucalyptus globulus*, and *Eucalyptus nitens* were established at initial stockings of 5,000; 7,500 and 10,000 trees ha^{-1} on marginal sites with important nutritional and hydric limitations in the Biobío Region, Chile. After 48 months, *E. camaldulensis* reached the highest biomass yield at initial stocking of 7,500 trees ha^{-1} (22.5 Mg ha^{-1}) on dry land granitic soils, and *E. nitens* reached 35.2 Mg ha^{-1} on sandy soils. Initial stockings and biomass yields were directly related, but strongly conditioned by mortality, where greater initial stocking concurred with greater mortality after 4 years. The collar diameter and total height growth was lower at higher stockings.

Keywords: Bioenergy; Growth and biomass yield; *Eucalyptus* spp.

PRIMEIRO CICLO DE CORTE DE CRESCIMENTO BIOMASSA ACIMA DO SOLO E PRODUTIVIDADE DE ENSAIOS DE DENDROENERGIA DE Acacia E Eucalyptus

RESUMO – O Chile tem um forte interesse na produção de biomassa com o objetivo de gerar bioenergia para cumprir padrões ambientais para a produção de energia limpa. No entanto, não há informações de produtividade ou produtividade disponíveis sobre plantações de culturas florestais estabelecidas em densidades de plantio elevadas, dedicadas à produção de energia. O objetivo do presente estudo foi fornecer resultados a longo prazo de estudos de pesquisa de culturas florestais de rotação curta, investigando o primeiro ciclo de corte, a produção de biomassa de espécies mais promissoras. As plantações de **Acacia melanoxylon**, **Eucalyptus camaldulensis**, **Eucalyptus globulus** e **Eucalyptus** nitens *foram estabelecidas em meias iniciais de 5.000; 7.500 e 10.000 árvores* ha^{-1} *em locais marginais com importantes limitações nutricionais e hídricas na Região Biobío, no Chile. Após 48 meses,* **E. camaldulensis** *atingiu o maior rendimento de biomassa na base inicial de 7.500 árvores* ha^{-1} *(22,5 Mg* ha^{-1}*) em solos graníticos de terra seca e* **E. nitens** *atingiu 35,2 Mg* ha^{-1} *em solos arenosos. As meias iniciais e os rendimentos de biomassa foram diretamente relacionados, mas fortemente condicionados pela mortalidade, onde maior estocagem inicial concordou com maior mortalidade após 4 anos. O diâmetro do colar eo crescimento da altura total foram menores nas meias mais altas*

Palavras-Chave: Bioenergia; Crescimento e produção de biomassa, **Eucalyptus** *spp.*

http://dx.doi.org/10.1590/1806-90882017000600008

1. INTRODUCTION

Forestry and reforestation activities help mitigate the effect of greenhouse gas emissions (Bustamante et al., 2014). Forestry crops intended for biomass production, defined in Article 12 of the Kyoto Protocol as Clean Development Mechanisms (Van Vliet et al., 2003), constitute an important source of bioenergy with reduced greenhouse emissions and may help to partially offset the large demand for fossil fuels (Lloyd and Subbarao, 2009). Thus, implementing biomass-oriented forestry crops is urgent, especially in developing countries (Lloyd and Subbarao, 2009).

Currently in Chile, biomass used for energy production comes from harvesting residues from traditional forestry operations and industrial processes (*e.g.* harvesting and milling operations). Yet, forestry crops intended for biomass production for bioenergy exist only at an experimental level. Worldwide, many studies have provided information on growth and biomass yield, at the experimental and operational levels for bioenergy production (Silver et al., 2015). Crops intended for biomass production (SRFC) are mainly grown in high initial density plantations (Parmar et al., 2015; Santangelo et al., 2015). Indeed In, the management of plantation density counts as a critical decision concerning SRFC (Pinkard and Neilsen, 2003), with direct implications for the optimization of different final products. An appropriate initial planting density is important economically (Bernardo et al., 1998; Pinkard and Neilsen, 2003), and the individual tree response to initial spacing has been widely studied (Pinkard and Neilsen, 2003; Harmand et al., 2004; Barton and Montagu, 2006; Wilkinson et al., 2007). The main objective of such research has been how stand density affects certain tree variables (*e.g.* diameter at various heights at level ground, total height, development of roots and branches) and variables at stand level (*e.g.* biomass, volume); these investigations cover numerous species, mainly the genus *Salix*, *Populus*, *Acer*, and *Eucalyptus*.

Plantations of *Eucalyptus* spp. intended for bioenergy have been established mostly in Australia, New Zealand, China, South America, the Mediterranean, and Africa (Niemistö, 1995; Sochacki et al., 2007). Species of this genus are characterized by rapid growth and high wood production, making them the primary choice for biomass production (Macfarlane et al., 2004; Parsons et al., 2004; Forrest and Moore, 2008). Numerous studies report the biomass yield of these species as short-rotation crops established at various stockings (Barton and Montagu, 2006; Sochacki et al., 2007; Forrest and Moore, 2008). In general, these authors agree that at higher initial stand densities higher levels of stand biomass obtain at the expense of lower individual tree diameter and height. The authors also coincide that biomass yield is maximized among initial stocking between 2,500 and 5,000 trees per hectare within a rotation of 3 to 6 years for these SRFC. The interaction of initial stocking, species, mortality rate and biomass yield has not been reported yet in dendroenergy crops established in Chile and is uncertain for marginal soils of central Chile proposed as key for development of these SRFC.

The objective of the present research was to develop first cutting cycle estimates of biomass production of SRFC established at different initial planting densities. Three species of *Eucalyptus* (*E. globulus*, *E. camaldulensis*, *E. nitens*) and one *Acacia* (*A. melanoxylon*) were evaluated after 48 months in biomass yield at two marginal dryland soils locations in the Biobío region of Chile.

2. MATERIALS AND METHODS

2.1. Trial characteristics and location

The study considered information from two contrasting productivity soil-site environments in central-south Chile; from Llohué (medium fertility site) (36.2938° S, 72.3822° O) located near the town of Ninhue (173 m asl),) and Santa Rosa (low fertility site) (37°03’33" S; 72°11’12" W) near Yungay (180 m asl).

The northern site was previously occupied by a 24-year-old *Pinus radiata* D. Don plantation with mean annual rainfall of 695 mm (80% concentrated in winter) and five dry months. Minimum, mean, and maximum mean annual temperatures at the site were 5.3°C, 11.3°C and 17.5°C, respectively. Topography is hillside with 10 to 20% slope, and soils are Alfisols of the Cauquenes soil series (Centro de Investigación de Recursos Naturales, 1999b) classified as Ultic Palexeralfs. The soil is made up of materials of granite origin with moderate acidic conditions and low organic carbon. Soils are deep (>120 cm), well drained, well structured, and show a clayey or silt-clayey surface horizon and clayey texture in depth (Centro de Investigación de Recursos Naturales, 1999a). The Santa

Rosa site's soil was used in the site past for a 22-year-old *P. radiata* plantation. The site experienced mean annual rainfall of 1048 mm and minimum, mean and maximum mean annual temperatures of 6.4ºC, 12.9ºC and 19.3ºC, respectively. The terrain is flat and soils deep (>150 cm) with a loamy texture on thein surface and a coarse sandy soil texture in depth. Soils were classified as Coreo series, belonging to the mixed thermal family of Dystric Xeropsamments (Entisol) (Centro de Investigación de Recursos Naturales, 1999b), derived from andesitic and basaltic sands.

The trial was established in August 2007 as a complete randomized block design (CRBD) with three replicates. Blocks were 75 m side squares (5625 m^2) consisting of nine internal square experimental units of 25 m sides (625 m^2) with 49 measurement trees and a buffer zone to reduce edge effects. At Llohué, three species (*A. melanoxylon*, *E. camaldulensis* and *E. nitens*) were established in each block at three initial stockings (5,000, 7,500, 10,000 trees ha^{-1}). At Santa Rosa, the trial consisted of a CRBD in split-plot with three species (*A. melanoxylon*, *E. camaldulensis*, *E. globulus*) established at the same three stockings. For *E. camaldulensis* and *E. nitens*, each sub-plot was made up of a mitigation zone of edge effect and a core plot with 45 measurement trees (five rows of nine trees each), whereas for *A. melanoxylon*, the core plot consisted of 15, 24, and 30 trees established at 5,000, 7,500 and 10,000 trees ha^{-1}, respectively. The split-plot design was planned to analyze time of coppicing considering annual harvests starting after the second year. Four months after establishing this trial, *A. melanoxylon* plots showed high levels of mortality, and these units were replanted and stand densities returned to the nominal stocking at eleventh months.

2.2. Measurement of variables and biomass determination per tree and surface unit

Individual tree measurements at each experimental unit took place in October and December 2007, July and December 2008, 2009 and 2010, and July 2011. At each measurement, time collar diameter (*D*) at 0.1 m above ground, diameter at breast height (*DBH*) once the trees grew above 1.3 m, crow diameter and total height of all trees were measured for each core experimental unit. In July 2008, 2009, 2010 and 2011 aboveground biomass was determined using destructive samples taken from three trees from buffer areas of each experimental unit. Collected trees from each species represented the diameter (*D*) and total height distribution of each species. Selected trees were cut at 0.1 m above ground, transported, and stored at 4ºC. The fresh material was dried at 105±2ºC to a constant dry weight. The total dry biomass per tree was determined by dry weighing each component (*i.e.* stem, branches and foliage) separately.

Data from the biomass sampling was used to adjust the relationship $\ln y = b_0 + b_1 \,\mathrm{Ln}(D^2 H)$ at tree level, corresponding to the logarithmic transformation of the model $y = \beta_0 (D^2 H)^{\beta 1}$ which intended to correct heteroscedasticity (Barton and Montagu, 2006). In those models, y represents the total aerial biomass of the tree or one of its components (g), *D* is the collar diameter (mm) and *H* the total height of the tree (cm); b_1 and b_2 are regression parameters. As the dependent variable of the model was expressed in logarithmic terms, it was not possible to consider additivity restrictions of tree biomass components (Parresol, 2001). Total and component biomass functions were fitted per species and initial stockings; an average fit was also done by species. Adjusted functions were used to estimate total and biomass components (stem, branches, foliage) in each experimental unit using collar diameter and total height as predictors. This procedure was carried out during each measurement, except the first (*i.e.* October 2007), when biomass was determined as the average of 10 plants per species, considering only the biomass of the tree, timber, and foliage. Total and biomass component per area unit were obtained by adding experimental unit plot individual trees and extrapolating the estimated biomass to hectare level considering the nominal initial stocking.

2.3. Data analysis

Both trials were evaluated independently using longitudinal analysis. The effect of species and stocking on mean collar diameter (*D*), mean tree height (*H*), and total and component biomass yields per hectare were determined using Tukey's test. All analyses were carried out using SAS (Proc REG and MIXED). The longitudinal analysis assumed an *R* matrix of heterogeneous covariance with a first-order autoregressive structure AR (1) in the mixed modeling procedure.

3. RESULTS

At both trials, the species effect was significant on most of the analyzed variables (Table 1 and Figure 1). Only stem biomass at Llohué did not differ significantly

Table 1 – Probabilities obtained in the longitudinal analysis carried out at Llohué and Santa Rosa trials.
Tabela 1 *– Probabilidades obtidos na análise longitudinal realizado em julgamentos Llohué e Santa Rosa.*

Site	Effect	Biomass (Mg ha^{-1})				*D* (mm)	H (cm)
		Total	Stem	Branch	Foliage		
Llohué	Block	0.4336	0.3512	0.4466	0.0002	0.2486	0.9295
	Month	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001
	Species	0.0270	0.0706	0.0325	<0.0001	<0.0001	<0.0001
	Stocking	0.3663	0.3417	0.6234	<0.0001	0.0843	0.8446
	Species×Stocking	0.7771	0.6941	0.7937	<0.0001	0.0747	0.0329
Santa Rosa	Block	0.8195	0.8209	0.7844	0.0094	0.0344	<0.0001
	Month	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001
	Species	0.0064	0.0140	0.0054	0.0004	<0.0001	<0.0001
	Stocking	0.9899	0.9151	0.9424	<0.0001	0.0874	0.0672
	Species×Stocking	0.8098	0.5119	0.9530	<0.0001	0.0067	<0.0001

between species. Initial stocking, however, significantly affected only foliage biomass. As expected, the longitudinal analysis revealed that crop age had a significant effect on all the variables analyzed at both sites.

At both trials, the species of *Eucalyptus* reached the higher biomass yield and significantly exceeded that of *A. melanoxylon*. In Llohué, *E. camaldulensis* reported the highest total biomass yield with 14.9, 22.5 and 20.3 Mg ha^{-1} at initial stocking of 5,000, 7,500 and 10,000 trees ha^{-1}, respectively (Table 2 and Figure 1). Meanwhile, in Santa Rosa, *E. nitens* yielded the highest total biomass with 23.4, 35.2, and 29.2 Mg ha^{-1}, respectively (Table 2 and Figure 1). Overall, the effect of initial stocking was not significant on the biomass yield and no clear relation between both emerged. This shows that interaction existed, as indicated by the significant interaction among species×stocking in foliage yield and mean height growth (Table 1).

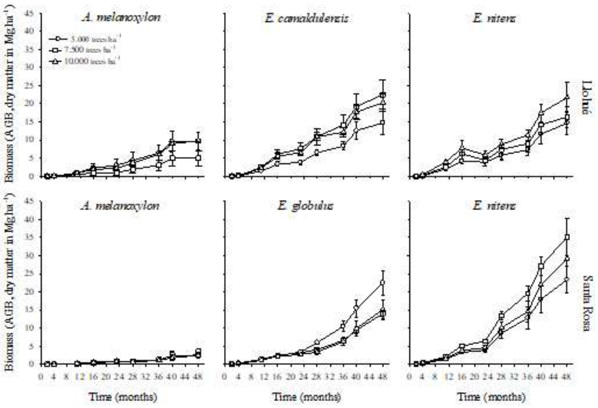

Figure 1 – Evolution of the total dry aboveground biomass yield (AGB, dry matter in Mg ha^{-1}) at Llohué and Santa Rosa. Vertical bars represent the standard error of the estimate for each age.
Figura 1 *– Evolução da produção total de biomassa acima do solo seco (BAS, de matéria seca em Mg ha^{-1}) pelo Llohué e Santa Rosa. As barras verticais representam o erro padrão de estimativa para cada idade.*

At both sites, growth in collar diameter (*D*) and total height (*H*) was greatest for *E. nitens* (Table 2). At Llohué, the growth of *E. nitens* was followed by *E. camaldulensis* and *A. melanoxylon*; the differences in *D* and *H* were significant among the three species. Although, the species did generally not show significant differences among initial stocking over growth in *D* and total height, they were inversely related to the initial stocking. *D* was similar among initial stockings, whereas *H* in *E. camaldulensis* at 7,500 trees ha^{-1} and *E. nitens* at 5,000 and 7,500 trees ha^{-1} differed significantly. At Santa Rosa, the growth of *E. nitens* was followed by that of *E. globulus*, then *A. melanoxylon*; the differences in *D* and total height were significant among the three species. *D* and *H* were significantly higher at 5,000 tress ha^{-1} for the *Eucalyptus*; no initial stocking effect was evidenced on *A. melanoxylon*.

In general, biomass accumulation per area unit for all species at both sites was still in the exponential growth phase (Figure 1). At Llohué, *E. camaldulensis* and *E. nitens* yields were higher, despite the lower biomass yield observed for all three stockings between months 16 and 23 which was related to the high mortality occurring in that period (Figure 3). At both sites, *A. melanoxylon* generated lower biomass yields as compared to those observed for the *Eucalyptus* species; this difference was even more evident in the sandy soils

Table 2 – Average biomass yield and growth obtained at Llohué and Santa Rosa 48 months after the establishment of the trials.
Tabela 2 – *Produção de biomassa média e crescimento obtido Llohué e Santa Rosa em 48 meses após o estabelecimento dos ensaios.*

Site	Biomass(Mg ha^{-1})	Stocking(tree ha^{-1})	*A. melanoxylon*	*E. camaldulensis*	*E. nitens*
Llohué	Total	5000	9.6 A b	14.9 A a	14.6 A a
		7500	5.0 A b	22.5 A a	16.3 A a
		10000	9.8 A b	20.3 A a	21.6 A a
	Stem	5000	5.3 A a	9.0 A a	8.4 A a
		7500	2.9 A a	14.2 A a	5.7 A a
		10000	4.8 A a	12.0 A a	8.9 A a
	Branch	5000	2.2 A b	3.2 A a	2.9 A a
		7500	1.1 A b	4.0 A a	3.9 A a
		10000	3.3 A a	4.0 A a	3.9 A a
	Foliage	5000	2.5 AB c	3.5 B b	4.2 C a
		7500	1.5 B c	5.0 A b	7.1 B a
		10000	3.1 A c	5.3 A b	9.3 A a
	D(mm)	5000	58.3 A b	59.3 A ab	67.7 A a
		7500	39.9 A b	59.5 A ab	64.2 A a
		10000	46.1 A b	51.2 A ab	63.5 A a
	H(cm)	5000	348.5 A b	398.2 A b	478.2 A a
		7500	276.7 A b	468.2 A a	477.8 A a
		10000	334.3 A c	403.3 A b	505.2 A a
			A. melanoxylon	*E. globulus*	*E. nitens*
Santa Rosa	Total	5000	2.6 A b	22.5 A a	23.4 A a
		7500	3.6 A c	14.0 A b	35.2 A a
		10000	2.5 A c	15.2 A b	29.2 A a
	Stem	5000	1.3 A b	10.4 A a	12.5 A a
		7500	2.0 A b	5.2 A b	30.6 A a
		10000	1.3 A b	3.3 A b	16.4 A a
	Branch	5000	0.6 A b	5.9 A a	6.0 A a
		7500	0.9 A c	4.3 A b	8.4 A a
		10000	0.5 A b	4.5 A a	7.1 A a
	Foliage	5000	0.9 A b	6.4 A a	6.1 B a
		7500	1.2 A c	5.0 B b	7.1 A a
		10000	0.9 A b	6.7 A a	7.0 A a
	D(mm)	5000	30.8 A b	62.2 A ab	76.9 A a
		7500	29.8 A c	53.4 AB b	71.0 A a
		10000	24.1 A c	43.0 B b	69.1 A a
	H(cm)	5000	214.5 A c	422.7 A b	511.9 A a
		7500	248.6 A c	368.0 A b	510.7 A a
		10000	200.9 A c	328.3 B b	496.8 A a

Different upper-case letters show significant differences between initial stockings; different lower-case letters show significant differences between species according to Tukey test.

of Santa Rosa. At both trials, for all species and stockings, both *H* and *D* were in the exponential growth phase.

At both trials and for all species, the percentage of participation of the three biomass components showed a similar trend. The proportion of biomass of each component varied as the crop aged. The proportion of foliage predominates initially, but diminishes, relative as stem and branch components increase over time. At Llohué, foliage biomass of *A. melanoxylon* and *E. camaldulensis* predominates only during the first four months of growth, exceeding in some cases 80%; for both species the foliage biomass was equaled at eighth growing month and later surpassed by stem biomass, whereas for *E. nitens*, the foliage biomass was equaled by that of the stem at month 36. At Santa Rosa, foliage biomass from *A. melanoxylon* was equaled by that of timber at month 24. The same applied to the *Eucalyptus* species at the time of the last measurement. At both sites, 48 months after the establishment of the trials, the proportion of biomass increased gradually, and

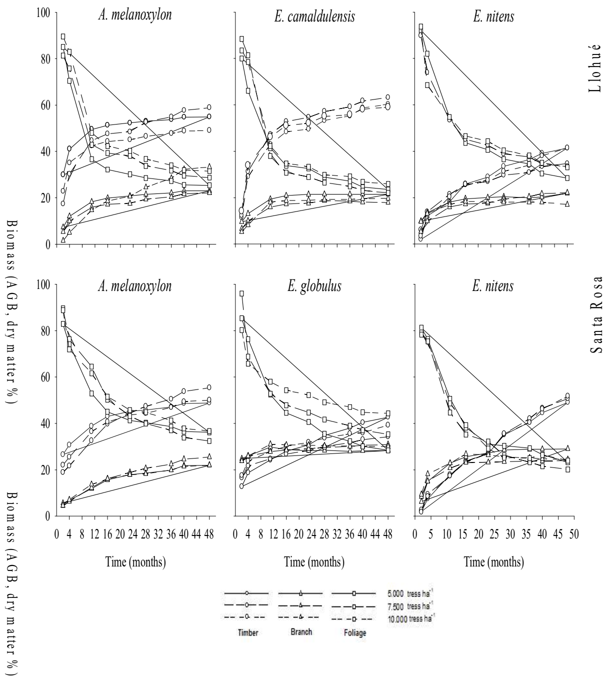

Figure 2 – Partitioning of biomass by hectare at Llohué and Santa Rosa.
Figura 2 – *Separação de biomassa por hectare em Llohué e Santa Rosa.*

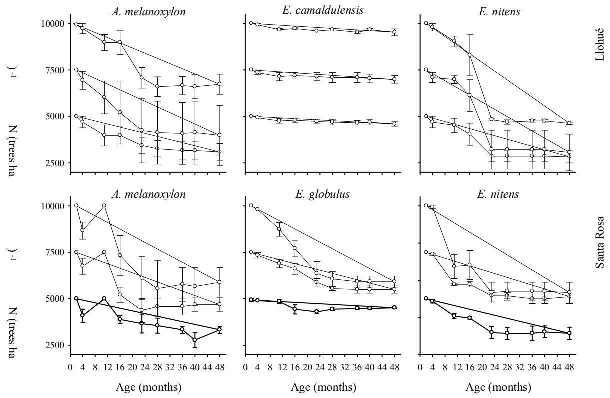

Figure 3 – Mortality observed in the dendroenergy trials at Llohué and Santa Rosa. Vertical bars represent the standard error of the estimate for each age.
Figura 3 – *Mortalidade observada nos ensaios de dendroenergia em Llohué e Santa Rosa. As barras verticais representam o erro padrão de estimativa para cada idade.*

both the proportion of foliage and branch tended to stabilize. Overall, at 48 months, stem was the component that contributed most biomass of the tree, followed by foliage and branches (Figure 2). At Llohué, the proportion of stem biomass both in *A. melanoxylon* and *E. camaldulensis* exceeded 50%, while that of *E. nitens* reached 40% for both stem and foliage biomass proportions. At Santa Rosa, the proportion of stem biomass both in *A. melanoxylon* and *E. nitens* exceeded 50%; in *E. globulus* it was about 40%.

Mortality varied between all four studied species (Figure 3). The lowest mortality rates and the lowest variation between experimental units were reached by *E. camaldulensis* at Llohué and *E. globulus* at Santa Rosa. This reveals the high level of persistence of *E. camaldulensis* and the high capacity for regrowth of *E. globulus*. At Llohué, mortality rates were lowest for *A. melanoxylon* and *E. nitens*, and at Santa Rosa for *E. nitens* and *A. melanoxylon*. At both sites, high mortality was registered at early ages, apparently due to problems in the plantation establishment phase, mainly related to the small size of the plants. Mortality rates were generally higher at greater stockings.

4. DISCUSSION

At both trials, *i.e.* Llohué and Santa Rosa, the *Eucalyptus* species grew in collar diameter (*D*) and *H* more than *A. melanoxylon*. At both trials, *E. nitens* registered the higher growth in both *D* and *H*, with significant differences among similar stockings. A study carried out in Cameroon, with 1050 mm precipitation and conditions similar to those of the present study, reported higher growth for *E. camaldulensis*; 40 months after the establishment of that trial, and at a stocking of 625 trees ha^{-1}, the approximate tree height was 10 m (Harmand et al., 2004). In another study in Tasmania, with soil derived from sands and climatic conditions similar to those of the Santa Rosa site, *E. globulus* reached a diameter of 50 mm and a height of 235 cm, 14 months after establishment in stocking of 1111 trees ha^{-1} (O'Grady et al., 2005); these values were higher than those observed herein. Similar results were reported by Honeysett et al. (1996), who also reported lower diameters than those obtained in the present study.

Although several authors have reported that *Acacia* species are highly adaptable to unfavorable environmental conditions (Nasser and Aref, 2014; Otuba and Weih, 2015), *A. melanoxylon* did not show good growth at either of the sites analyzed. One factor that could have negatively influenced both growth and survival for *A. melanoxylon*, especially at Santa Rosa, was the small size of the plants at time of planting. Plants with little root biomass could not withstand the hydric deficit and high surface temperatures of the sandy soil at Santa Rosa in summer. Numerous investigations provide information on biomass yield for these and other species (Hunter, 2001; Sims et al., 2001; Forrest and Moore, 2008), showing a variety of results that relate closely to site quality and, specifically, hydric deficits (Harmand et al., 2004; Wilkinson et al., 2007). Studies of *E. globulus* plantations in Mediterranean climates show that growth, especially in the earlier stages, is limited more strongly by hydric stress than by nutritional stress (Poersch et al., 2017).

In the present study, *Eucalyptus* species obtained the highest biomass yields. At both trials, the biomass of the *Eucalyptus* species significantly exceeded that of *A. melanoxylon*, in line with findings by Harmand et al. (2004), who reported higher biomass yields for *E. camaldulensis* than for *A. polyacantha*. In this study, at 7,500 trees ha^{-1} *E. camaldulensis* and *E. nitens* showed the highest average yield (22.5 and 35.2 Mg ha^{-1}) 48 months after the establishment of the trials. In turn, (González-García et al., 2016a) reported an annual production of only 13.7 Mg ha^{-1} (lower than that found herein) seven years after establishing the plantation. According to Sochacki et al. (2007), *E. globulus* plantations at 4,000 trees ha^{-1} accumulated 16.6 Mg ha^{-1} of dry material after the plantation's third year. For *E. camaldulensis*, Louppe et al. (1998) reported an annual production of 10.5 Mg ha^{-1} six years after establishing the plantation. In the tropical woods of Congo, with 1250 mm of annual precipitation, Laclau et al. (2000) obtained 12 Mg ha^{-1} per year^{-1} for seven-year-old *Eucalyptus* hybrid trees. In a trial carried out with *E. camaldulensis* in arid zones (600 mm of annual precipitation), Bernardo et al. (1998) reported average yields of 30.7 Mg ha^{-1}, 41 months after the establishment of the trial.

Essentially, the greater the initial plantation density the lower *D* and *H*. This tendency, which has also been reported in other studies (Barton and Montagu, 2006; Wilkinson et al., 2007), was found in all species studied at both trial sites. However, at Llohué, *E. nitens* registered its greater height at the highest stocking, a result similar to that obtained by Srivastava et al. (1999), who assured that the diameter and total height of *Terminalia arjuna* increased along with stocking at densities between 10,000 and 50,000 trees ha^{-1}. A study with *E. nitens* established at densities between 833 and 1,333 trees ha^{-1} by Pinkard and Neilsen (2003) concluded that the diameter of the trees was not affected by the stand density before the fifth year of growth, although those authors also mentioned that, at high plantation density levels, the effect could be manifested earlier, in line with the results of our study. *E. camaldulensis*, established at 7,500 trees ha^{-1} at Llohué, showed more growth in *D* and *H*; these results were most likely influenced by external factors not controlled in this trial. Jha (2017) noted that the growth tendencies for these variables were not clear in the first 22 months after establishing the plantation. Other studies have shown highly variable growth in young plantations when the site was not totally occupied (Fredericksen and Zedaker, 1995). Crow et al. (2016) indicated that the total occupation of the site by the root system did not occur before the fourth year.

Although 48 months after establishing the trial, a higher biomass yield per area unit was observed at medium initial densities, no significant effect was detected. This result may be explained by the high variability of *D* and *H* in the early stages of crop growth (Srivastava et al., 1999; Pinkard and Neilsen, 2003). At Santa Rosa, the biomass yield of *E. globulus* decreased as stocking increased, a result explained by the much smaller size of the trees established in those experimental units (Table 2). Coinciding with this, some authors have also reported such contrasting tendencies. Bernardo et al. (1998) reported similar results in trials with *E. camaldulensis* and noted, as did Barton and Montagu (2006), that higher aerial biomass yields were achieved at lower plantation density levels. In a study realized in *Salix viminalis*, Wilkinson et al. (2007) found that more biomass was generated with 20,000 trees ha^{-1} than with 25,000 trees ha^{-1}, although these differences were not significant. As in this study, Harmand et al. (2004) attributed such abnormalities in biomass yield per surface unit to the difference generated by the stocking in trees dimensions. Thus, the appropriate plantation density can maximize the total stand biomass (Pinkard and Neilsen, 2003).

As plantation age increased, stem biomass increased significantly at both trials, but the opposite occurred with foliage biomass. The contribution of branches to total tree biomass continued to increase, although not at the same speed as that of the stem. These results agreed with those reported by González-García et al. (2016b), who noted that increased tree growth or increased biomass production with age led to an asymptotic decline in the contribution of the foliage and fine and medium roots to the total biomass, whereas the contribution of timber, branches, and thick roots increased significantly.

Survival varied between sites. At Santa Rosa, mortality was higher than at Llohué, apparently due to the higher hydric deficit of the former. *A. melanoxylon* was the most sensitive species, which could not withstand the hydric stress to which it was subjected at the beginning of the plantation (*i.e*. fourth month), probably due to the small size of the plants at the time of plantation, which substantially conditioned the survival of the plantation; apparently these small plants were unable to withstand the strong drought and high surface temperature during summer. Despite this and after replanting, *A. melanoxylon* was able to endure at the site, exhibiting mortality rates similar to those observed in the *Eucalyptus* species. These results, which agreed with those of other authors studying various *Acacia* species from establishment, highlighted the adaptive capacity of this genus to unfavorable conditions (Hussain and Gul, 1991; Aref et al., 2003). At both sites, mortality increased with higher initial stocking, yielding results similar to those reported by Srivastava et al. (1999). Apparently, the different levels of survival between sites were due to different site conditions: strong hydric stress and high surface temperatures during summer diminished survival rates at Santa Rosa. These studies revealed the importance of the site for species survival (González-García et al., 2016a).

5. CONCLUSIONS

Forty-eight months after the establishment of the plantation, the total aboveground biomass yields from the *Eucalyptus* species were significantly higher than those of *A. melanoxylon*; *E. camaldulensis* and *E. nitens* established at Llohué and Santa Rosa trials were higher, respectively. The yield did not differ significantly between the three *Eucalyptus* species, indicating that the species with the highest regrowth capacity would be the most appropriate to establish as a dendroenergy crop, since this ability would allow many short-rotation cycles after a single initial establishment.

Forty-eight months after establishing the plantation, growth in *D* and *H* was significantly higher for the *Eucalyptus* species than for *A. melanoxylon*. Nonetheless, we cannot suggest to not use the latter species in dendroenergy crops since this result may have been due to differences during the establishment phase. At Llohué, the *D* growth for *E. nitens* was significantly greater than for *E. camaldulensis*; these two species did not differ in total height. At Santa Rosa, for most densities, growth in *D* and *H* was significantly higher in *E. nitens* than in *E. globulus*.

At both trials, biomass yield tended to increase along with stockings, but the difference amongst stocking levels was not significant. Growth in *D* and *H* inversely related to plantation density, but in most cases the effect was insignificant.

The biomass components varied between species and sites. At Llohué, after 48 months of growth, stem contributed the most to total tree biomass, followed by foliage and branches. To date, stem contributed more than 50% of the total biomass. At Santa Rosa, stem was the only main component for *A. melanoxylon*; for the *Eucalyptus* species, similar biomass proportions were registered for all three components. The dynamics of the components varied between sites. In the first months of growth, for all species, foliage made the highest contribution to total biomass. As crops grew, stem biomass increased in importance; this effect was observed later at Santa Rosa, the site with greater hydric stress in summer.

The success of a plantation for biomass production, especially during the first four months of growth, is closely related to site conditions and most likely to the initial size of the plants. The results of these trials show that the site strongly conditions the establishment, growth, and biomass yields of a plantation for purposes of dendroenergy. The adverse effect of the site could be reduced if the crops were established with good quality, adequately sized plants.

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