iForest
Biogeosciences and Forestry

Research Article
doi: 10.3832/ifor4040-015
vol. 15, pp. 433-443

Impact of rotation length of *Eucalyptus globulus* Labill. on wood production, kraft pulping, and forest value

Fernando Resquin [(1)],
Ismael Fariña [(2)],
Cecilia Rachid-Casnati [(1)],
Agustín Rava [(2)],
Javier Doldán [(2)],
Andrés Hirigoyen [(1)],
Fiorella Inderkum [(3)],
Sofía Alen [(3)],
Virginia Morales Olmos [(4)],
Leonidas Carrasco-Letelier [(5)]

Most of the wood from *Eucalyptus globulus* Labill. plantations in Uruguay is harvested for pulp industry at an average age of 11 years. In this study we evaluated the volume and quality of the wood produced and the economic return for owners using different rotation length (from 6 to 13 years) and two different provenances (Jeeralang, Australia and Chivilingo, Chile) in experimental plots planted at two different sites (southwest and southeast of Uruguay). Silvicultural practices, industrial process, and economic aspects of the plantations were evaluated by measuring the following variables: survival, individual and per hectare growth, basic density, cellulose yield, wood consumption, cellulose production per hectare, dry solids content, fiber length, paper resistance, internal rate of return, and soil expectation value. The results showed that an increase in the harvest age generates: (i) an increase in the production of wood and cellulose per hectare at decreasing rates; (ii) an increase in wood density and yield; (iii) a reduction in the consumption of wood and solid contents in the cooking liquor; and (iv) a reduction in economic profitability at the farm level. No differences were found in the fiber length and resistance properties of the paper from wood harvested at different ages.

Keywords: *Eucalyptus globulus*, Harvest Age, Pulping Kraft, Fiber Length, Forest Value

Introduction

In Uruguay, the production of wood for cellulose pulp relies heavily on *Eucalyptus grandis, E. dunnii*, and *E. globulus* plantations (MGAP/DIEA 2020) because of their growth rates and technological properties (*e.g.*, high density of wood, cellulose yield), which allow the manufacturing of high-quality paper demanded by the international market (Kibblewhite et al. 2001). Despite several phytopathological problems occurring in Uruguay, *E. globulus* plantations have been widely settled in the southeastern region of the country mostly using two provenances (Jeeralang, Australia; Chivilingo, Chile) and a rotation regime with regrowth management. However, the wood of this species is still highly demanded by the international market due to its relative ease in the Kraft pulping process, its highly efficient wood conversion rate to cellulose pulp, and its suitable properties for the manufacture of tissue paper (Carrillo et al. 2015).

The age of harvesting is one of the most important silvicultural management practices affecting the volume of produced wood, wood technological properties (Magaton et al. 2009), and, therefore, the economic return (Villacura 2012). This involves that the variation of the rotation length can improve the properties of pulpwood and paper (Megown et al. 2000), depending on the impact of this management practice on profitability in the long run, and taking into account silvicultural and industrial phases.

Several studies showed that in the early tree development (6-15 years of age) significant changes occur in the physical and chemical properties of eucalypt wood (Magaton et al. 2009, Kibblewhite et al. 2001). These transformations are associated with the change that occurs as the tree grows from the juvenile to adult phase at about 8-10 years of age, depending on the species.

During the transition from juvenile to adult wood, many changes in the anatomical parameters occur, both in physical and chemical compositions (Xie et al. 2000). In the early years of eucalypt growth, there are increases in holocellulose content, basic density, length and thickness of the fiber wall, and reductions in the frequency of vessels and the contents of lignin and extractives (Alencar 2002, Silva 2011). These modifications are due to changes in the cambial meristematic tissue (which determines the secondary growth) that occur with the aging process. In most cases, these alterations result in an increase in cellulose yield, a reduction in wood con-

(1) Programa Nacional de Investigación Forestal, INIA - Instituto Nacional de Investigación Agropecuaria, Ruta 5 km 368, CP 45000,Tacuarembó (Uruguay); (2) Departamento de Proyectos Forestales, Laboratorio Tecnológico del Uruguay, Avenida Italia 6201, 11500, CP 12900, Montevideo (Uruguay); (3) Facultad de Ciencias Agrarias de la Universidad de la Empresa, Av. Dr. Luis Alberto de Herrera 2890, CP 11600 Montevideo (Uruguay); (4) PDU Departamento de Ciencias Económicas, CENUR Noreste - Universidad de la República, CP 45000, Tacuarembó (Uruguay); (5) Programa Nacional de Investigación en Producción y Sustentabilidad Ambiental, INIA - Instituto Nacional de Investigación Agropecuaria, Ruta 50 km 11, CP 70000, Colonia (Uruguay)

@ Fernando Resquin (fresquin@inia.org.uy)

Received: Dec 17, 2021 - Accepted: Aug 08, 2022

Citation: Resquin F, Fariña I, Rachid-Casnati C, Rava A, Doldán J, Hirigoyen A, Inderkum F, Alen S, Morales Olmos V, Carrasco-Letelier L (2022). Impact of rotation length of *Eucalyptus globulus* Labill. on wood production, kraft pulping, and forest value. iForest 15: 433-443. - doi: 10.3832/ifor4040-015 [online 2022-10-20]

Communicated by: Rodolfo Picchio

sumption, and an improvement in the resistance properties of the paper obtained (Morais 2008). The use of high-density wood allows an increase in chip load per unit volume in the digester, which would allow a high cellulose yield (Morais et al. 2017). According to these authors, it is expected an increase in the wood density with age, within certain age ranges, leading to an increase in the pulp yield. However, opposite results have also been reported (Miranda & Pereira 2002). Additionally, an excessive wood density could hamper chips impregnation by the cooking liquor. This would require applying harsher cooking conditions (higher temperature and/or longer cooking time or alkali charge), leading to a reduction in yield and an increase in wood consumption (Mokfienski et al. 2008). High values of wood density consume more energy during chipping, promote the generation of chips of uneven size and prevent homogeneous conditions in chemical pulping (Silva 2011). On the other hand, an increase in the thickness of the fibers (associated with the increase in wood density) causes an increase in energy requirements during refining, making the union between the fibers more difficult. This can be an advantage to produce sanitary papers, which require high specific volume. It has also been identified that the high positive correlation between wood age and holocellulose content is accompanied by a negative correlation between wood age and the extractives and lignin affecting cellulose yield (Xie et al. 2000, Gomide et al. 2005). The removal of both lignin and extractives requires alkali consumption or determine hard kraft pulping conditions, which could promote the degradation of the more hydrolysable cellulose and essential hemicelluloses and increase the solids content of the cooking liquor (Santos 2005). The lignin content does not always show a close relationship with the yield; the syringyl:guaiacyl ratio of the wood has been identified as a better yield predictor (Morais 2008, Carrillo et al. 2015, Río et al. 2005, Reina et al. 2014). On the other hand Morais et al. (2017) determined a decrease in lignin content in ages 1-8 years.

The aforementioned age-related changes are closely related to the silvicultural phase (*e.g.*, production of dry matter per hectare and per unit of time), with repercussions in the industrial phase (*e.g.*, consumption of reagents and wood during pulping, content of solids in liquor, refining requirements), and in the characteristics of the paper obtained. To define the best harvest age for forest production, it is important to consider the gravimetric yield, because it depends on volume growth, wood density, and cellulose yield. According to Lopes et al. (2017), it is likely to obtain increases in biomass production beyond the stagnation of growth in volume, due to an increase in the wood density with age.

All the aforementioned factors affect the profitability of pulp and paper production since wood and reagents represent up to 50% of the total operational costs of a pulp mill (Dieste et al. 2019). Therefore, to maximize the net benefits of cellulose pulp production (*i.e.*, wood production and industrial conversion), a key goal is to choose the best harvest age for forest plantation.

It was hypothesized that rotation age affects the properties of the wood produced, pulp and paper production, and the economic value of the forest. To test this hypothesis, this study: (i) estimated the timber growth and pulp properties of *E. globulus* at different harvest ages in southeast and southwest Uruguay with two origins of commercial seed; (ii) identified the harvest ages with high pulp yield per hectare and low wood consumption; and (iii) estimated the economic results of the plantations at each rotation age for each situation. The information obtained in this work allows to optimize the harvest age considering all the aspects of the forestry-industrial value chain. This information can be used by forestry producers in different country regions to choose the rotation length with the the best economic result, considering the growth and the price obtained for the wood based on its pulpable properties. This study reflects the prevailing production situations in terms of the genotypes used and regions of the country planted with this species.

Materials and methods

Study area

Two sources of seed were tested in two sites (Jeeralang, a native forest in Victoria, Australia; and the Chivilingo seed orchard, from Monte Águila company in the VIII region of Chile) on two forest soils of the southwest (SW) and southeast (SE) regions of Uruguay (Fig. S1 in Supplementary material). Commercial plantations were carried out during the spring and autumn months between 1999 and 2001 with plants from nurseries. The seeds were sown in the nursery in the previous months of the mentioned years and later taken to the field to be planted. The plots were initially made up as follows: 25 rows of 50 trees; 30 rows of 50 trees; 30 rows of 71 trees (average) and 30 rows of 46 trees for Chivilingo/Jeeralang on the SW and Chivilingo/Jeeralang on the SE, respectively. The initial number of trees per hectare at the start of the evaluations was: 960, 1364, 1664 and 1415, respectively. The evaluations were carried out during the years 2008, 2010, and 2012 on sites considered representative in terms of the productivity of the companies, silvicultural systems, and forest sites. The main characteristics of the sites (plots, ages of the samplings) are shown in Tab. S1 (Supplementary material). The mean annual temperatures for the SW and SE zones are 17 °C and 18 °C, respectively, with rainfall of 1200-1300 mm per year (Castaño et al. 2011). The climate is subtropical temperate without dry season (Cfa), according to the classification Köppen-Geiger (Kottek et al. 2006).

Experimental design

A completely randomized design with 15 repetitions in each age was used to evaluate the effect of the harvest age with two seed sources in two forest regions. A systematic sampling of trees was carried out in plots of ~1 ha, randomly assigned in each site and for each age. The harvest of the trees in each plot was carried out in a period of one week considering an age range from 6.6 to 13 years.

Tree sampling and growth measurement

In the aforementioned years the diameter at breast height (*DBH*, cm) was measured with a diameter tape in all trees, but total height (*Ht,* m) was measured in approximately 1/3 of the trees in the plot with a Vertex hypsometer. For each inventory 5 diameter classes of 3 cm amplitude were established for the selection of the trees to be sampled, disregarding those with *DBH* < 10 cm. Twenty trees with a *DBH* closer to the mean in each class were measured with a Pilodyn densitometer. The penetration values were ranked, and 15 trees from the high, middle, and low ranges that were close to the average of the previous 100 trees evaluated, were cut. The trees were harvested manually with a chainsaw and with this equipment the samples were extracted for laboratory analysis. The number of felled trees within the groups with high, medium and low values of Pilodyn penetration was in proportion to the Basal Area (*BA*, m^2) that each of the classes represents in the total *BA* of the plot. Each tree from each 15-tree group was measured for diameter with and without bark at the base, at 0.7 m, 1.3 m, and then every 1 m up to commercial height (*Hc,* m) (diameter of 6 cm with bark). This data was used to calculate the individual volume (*Vi,* m^3) using the Smalian's formula, which was later used to adjust volume estimation models. From each tree, a log was extracted from the height corresponding to the *DBH* and 1 m long for the pulping analysis.

Wood density and stem weight

One disk-type samples were extracted from each tree at the height of the *DBH* measure, at 50% and 75% of H_c to determine the weighted basic density of each tree (*Wdpond,* g cm^3). The *Wdpond* of each tree was estimated according to eqn. 1 (Santos 2011):

$$Wdpond=\frac{A_0 Wd_0+A_{50} Wd_{50}+A_{75} Wd_{75}}{A_0+A_{50}+A_{75}} \quad (1)$$

where *Wdpond* is the basic wood density weighted for each tree, *A* is the cross-sectional area of the disk at each height (0, 50 and 75% of the *Hc*), and *Wd* is the wood density of each disk at each height (0, 50 and 75% of the *Hc*). The weight of the individual stem (*Wi*, kg) was calculated as the product of *Vi* (converted to cm^3) and *Wdpond.*

Fiber length

A second disc-type sample was extracted from the same positions as those indicated in the previous point to measure the fibers length (*Fl*, µm) according to the TAPPI (2006). To measure the *Fl* in each tree, three areas were identified in the pith-bark direction called A, B, and C, respectively. Disks extracted from these were placed in test tubes for maceration for 48 h at 60 °C in a solution of 1:1 (v/v) acetic acid (conc): hydrogen peroxide (conc). The *Fl* was measured by an image acquisition software linked to a Nikon Eclipse® E800 microscope (Nikon Corp., Tokyo, Japan) after washing fibers with water. From the height of 1.3 m a 1-m log was extracted for pulping, bleaching, and paper property analysis.

Pulping, bleaching and paper properties

Each log was chipped and screened through a 10-29 mm net in a vertical disk chipper (Kumagai) and used to form a composite of the 15-tree sample. The Kraft pulping tests were carried out in a rotary digester with 4 capsules having a capacity of 200 g of dry wood. The cooking conditions were tested with a kappa index (*KI*) of 20 ± 1, 165 °C maximal temperature, 25% of sulfidity, 90 minutes of maximum time, 50, liquor/wood ratio 3.5/1, active alkali (*Aa*, % – percentage as Na_2O) variable. As a result of these analyses, it was determined that Total and Screened yield (*Yt* and *Ys*, %) and *KI* were in accordance with the TAPPI (2006). With the values obtained the Specific consumption (*Sc*, m^3 cel ton^{-1}) and Solid content (*tss*, %) were estimated as follows (eqn. 2, eqn. 3):

$$Sc = \frac{1}{Wdpond \cdot Ys} \quad (2)$$

$$tss.odt = \frac{(100 - Yt) + Aa}{Ys} \quad (3)$$

where *tss.odt* is the dry solids content per ton of cellulose, and *Yt* is the total yield (%).

The subsequent bleaching of the pulp was followed an elemental chlorine free (ECF) sequence (Tab. S3 in Supplementary Material). Three refining intensities were used: 0, 1000, and 3500 revolutions with a PFI mill according to the LATU procedure based on the ISO 5264 standard (ISO 2002). The sheets were made manually in accordance with the ISO 5269 norm (ISO 2005) in LATU's facilities. These sheets were assessed to determine grammage, tensile strength, and tear strength in accordance with the ISO 5270 norm (ISO 1998). To compare the obtained sheet resistance, tensile (*tens*, N m g^{-1}) and tear index (*tear*, mN m^2 g^{-1}) were determined at two levels of drainability: 25 Schopper-Riegler (*SR*°) and 400 Canadian Standard Freeness (*CSF*).

Fitting individual height, volume, and weight equations

The equations to estimate the *Ht* (Tab. S2 in Supplementary material) were adjusted with a set of 3981, 2869, 2971, and 3819 data for plots Jeerlang and Chivilingo seeds in the SW and SE, respectively, with the three ages considered together. In fitting the *Vi* and *Wi* equations, 11 models were evaluated using data from 45 trees (15 for each age) for each seed origin and site. Various models reported in the literature were fitted to the data (Tab. 1). From the set of models fitted for each variable, the one with the best prediction capacity for each seed origin and site was selected based on the adjusted R^2, root mean square error (*RMSE*) and bias (*Bias*). The performance of the models was also evaluated graphically through the frequency and distribution of the standardized residuals as well as the distribution of the estimated values *versus* the observed values (Fig. S2 to S5 in Supplementary material).

Volume, weight of wood, and cellulose per hectare

Using the models selected for the estimation of *Ht, Vi, Wi,* and Survival (%), we calculated the Volume per hectare (*Vh*, m^3), Weight per hectare (*Wh*, ton) and Medium Annual Increment of volume and weight (*MAI*, m^3 ha $year^{-1}$ and ton ha $year^{-1}$, respectively). The *Vh* and *Wh* values were calculated from the sum of the *Vi* and *Wi* values in each plot and subsequently their equivalence to the hectare. With the *Wh* data and *Ys*, the Cellulose production per hectare (*Ch*, ton) and the respective *MAI* were estimated. The model adjustment procedures were performed in R version 4.0.3 (R Core Team 2020).

Forest value

For each of the origins and sites, the Net Present Value (*NPV*, US\$ ha^{-1}) was calculated. The *NPV* is defined as the discounted cash flows of revenues and costs. To compare the economic value for different rotation ages for each site, the Soil Expectation Value (*SEV*, US\$ ha^{-1}) was calculated. The calculation of the *SEV* was carried out according to (eqn. 4):

$$SEV = \frac{NPV(1+i)^n}{(1+i)^n - 1} \quad (4)$$

where *NPV* is the net present value, *i* is the discount rate (%), and *n* is the number of years.

In all cases, three rotations were considered, assuming that both costs and prices remain unchanged during the period analyzed. Wood volume growth levels in the second and third rotation were assumed to be 70% of the growth level obtained in the first rotations based on commercial results with these genetic materials (Tab. S4 in Supplementary material).

It was assumed a nominal interest rate of 7%; plantation costs were 1555 US dollars per hectare and included weed and ant control, for the second and third rotations a replanting cost of 188 US dollars per hectare was assumed. Additionally, an annual management cost of 15 US dollars per hectare was assumed. These values were obtained from commercial companies that establish plantations on a large scale in the

Tab. 1 - Selected models of *Ht, Vi,* and *Wi* for seed origin and site evaluated, with all harvest ages combined. (exp): number *e*.

Sites	Models	Parameter estimated	R^2adjusted	RMSE	Bias
Jeeralang SW	$1.3+(0.224280+1.273639/DBH)^{(-2.5)}$	Ht	0.77	1.89	$3.23 \cdot 10^{-3}$
Jeerlang SE	$34.9163 \cdot exp^{(-9.2953/DBH)}$	Ht	0.73	1.58	$-3.69 \cdot 10^{-03}$
Chivilingo SW	$DBH/(0.508279+0.025815 \cdot DBH)$	Ht	0.59	2.07	$1.49 \cdot 10^{-03}$
Chivilingo SE	$-11.8122+11.5313 \cdot \ln(DBH)$	Ht	0.74	2.06	$-3.97 \cdot 10^{-04}$
Jeeralang SW	$exp(-10.6078+ 1.7462 \cdot \ln(DBH)+ 1.3001 \cdot \ln(Ht))$	Vi	0.95	0.035	$2.51 \cdot 10^{-04}$
Jeerlang SE	$3.511e^{-05} \cdot ((DBH^2) \cdot Ht)^{0.9.801}$	Vi	0.99	0.011	$-1.37 \cdot 10^{-05}$
Chivilingo SW	$2.249e^{-05} \cdot (DBH^{1.718}) \cdot (Ht^{1.361})$	Vi	0.98	0.018	$-1.66 \cdot 10^{-4}$
Chivilingo SE	$2.860e^{-05} \cdot (DBH^{1.908}) \cdot (Ht^{1.087})$	Vi	0.98	0.024	$-3.4 \cdot 10^{-04}$
Jeeralang SW	$exp(-5.6819 + 1.9072 \cdot \ln(DBH) + 1.5675 \cdot \ln(Ht))$	Wi	0.95	20.5	0.210
Jeerlang SE	$exp(-4.39598 + 1.02825 \cdot \ln(DBH^2 \cdot Ht))$	Wi	0.97	9.8	0.154
Chivilingo SW	$0.010483 \cdot (DBH^{1.927113}) \cdot (Ht^{1.201616})$	Wi	0.96	15.8	0.010
Chivilingo SE	$exp(-4.9493 + 1.0823 \cdot \ln(DBH^2 \cdot Ht))$	Wi	0.97	18.4	0.060

Tab. 2 - Individual growth and survival of each seed source and site in the range of ages evaluated.

Seed origin	Sites	Age (years)	DBH (cm)	Ht (m)	Vi (m³)	Survival (%)
Jeeralang	SW	8.6	18.2^{c}	22.1^{c}	0.250^{c}	75
		10.7	19^{b}	22.6^{b}	0.273^{b}	72
		13.0	20.5^{a}	23.6^{a}	0.330^{a}	67
	SE	7.6	16.3^{b}	19.2^{a}	0.167^{b}	86
		9.8	17.2^{a}	19.9^{a}	0.194^{a}	84
Chivilingo	SW	6.9	19.3^{c}	18.6^{c}	0.214^{c}	67
		9.1	20^{b}	19.2^{b}	0.239^{b}	66
		11.4	21.8^{a}	20.4^{a}	0.302^{a}	60
	SE	6.6	16.6^{c}	19.9^{c}	0.178^{c}	71
		8.7	18.1^{b}	21.2^{b}	0.227^{b}	69
		11.1	20.2^{a}	22.6a	0.306^{a}	66

areas that comprise the regions evaluated in this study.

The model developed by the INIA Forestry Program for *E. globulus* was used (Hirigoyen et al. 2018) to estimate annual volumes per hectare for each age from 6 to 13 years in each plot.

Comparison timber growth and pulping properties between rotation ages

The variables analyzed were: diameter at breast height (*DBH*), total (*Ht*) and commercial height (*Hc*) considering a minimum diameter of 6 cm over bark, individual volume (*Vi*) and weight (*Wi*), survival, volume per hectare (*Vh*) and weight per hectare (*Wh*), average annual increase in the volume and weight (*MAIv*, *MAIw*), wood density weighted (*Wdpond*), total yield (*Yt*) and screened yield (*Ys*), wood consumption (*Sc*), cellulose production per hectare (*Ch*), cellulose increasing average annual (*MAIcel*), solids in cooking liquor (*tss*), fiber length (F_l), tensile index (*tens*) and tearing of sheets (*tear*).

The analysis of variance to evaluate the effect of the harvest age in each site and seed origin was carried out for the following variables: *DBH*, *Ht*, *Vi* and *Wd*. Normality, homogeneity, and independence of the errors were analyzed through the Shapiro-Wilk or Kolmogorov-Smirnov tests, Brown-Forsythe test, and graphical analysis, respectively. When these parametric statistic assumptions were verified, comparison between treatments (ages within sites) was performed for each assessed variable using the *F* test and subsequent comparison of means using the *post-hoc* Tukey test. In other cases, a non-parametric Kruskal-Wallis analysis of variance was used followed by the Dunn test, using a probability level of 5% in all cases. Multiple correlations between the following sets of variables were calculated considering the three ages together: (i) *Sc*, *Wdpond* and *Ys* and (ii) *Ch*, *Wdpond*, *Vh* and *Ys*. All analyses were carried out using the software Statistix® v. 10 (Analytical Software Inc., Tallahassee, FL, USA).

Results

Production per hectare and individual production

Individual growth of the two seed origins at two evaluated sites showed a significant increase in *DBH*, *Ht*, and V_i with an increase in harvest age. The increase of Chivilingo was greater than others in the SE zone with levels of 22, 14, and 72% *DBH*, *Ht*, and *Vi*, respectively for ages 11.1 *vs.* 6.6 years (Tab. 2). In all cases, a larger reduction in survival was observed in the SW but there were no statistical differences. The performance in terms of *Vh*, *Wh*, and *Ch* for the Jeeralang provenance was similar at both sites, with decreased rates at all the harvest ages (Fig. 1a). Chivilingo provenance showed greater increases in *Vh*, *Wh*, and

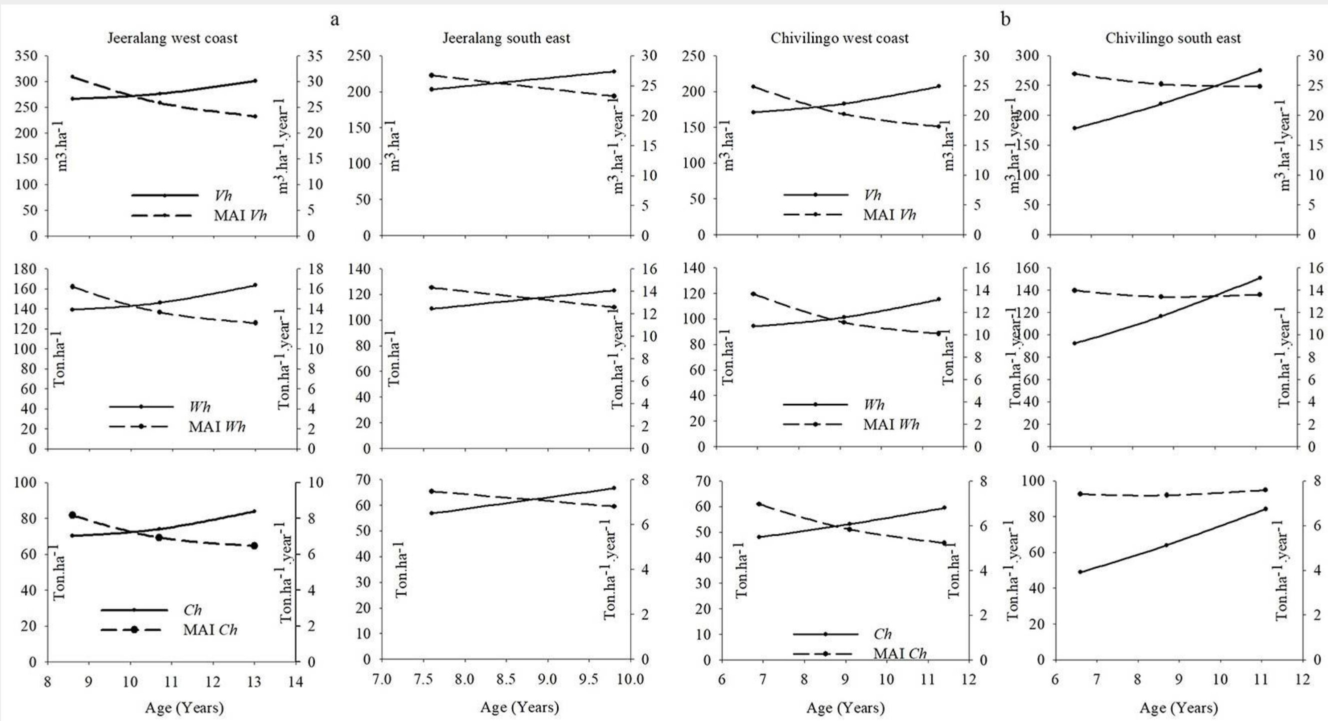


Fig. 1 - Accumulated values of *Vh*, *Wh*, and *Ch*, and the respectives *MAI* of Jeeralang (a) and Chivilingo (b) seed sources in the SW (left) and SE (right).

Fig. 2 - *Wdpond* and *Ys* screened for the two seed origins and sites at different harvest ages.

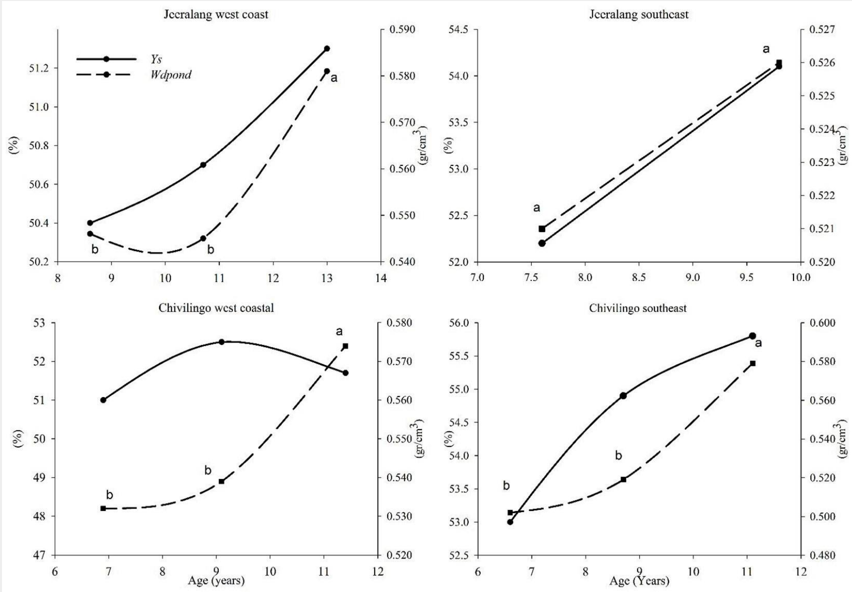


Fig. 3 - *Ys*/*Aa* ratio for the two seed origins and sites for the series of studied harvest ages.

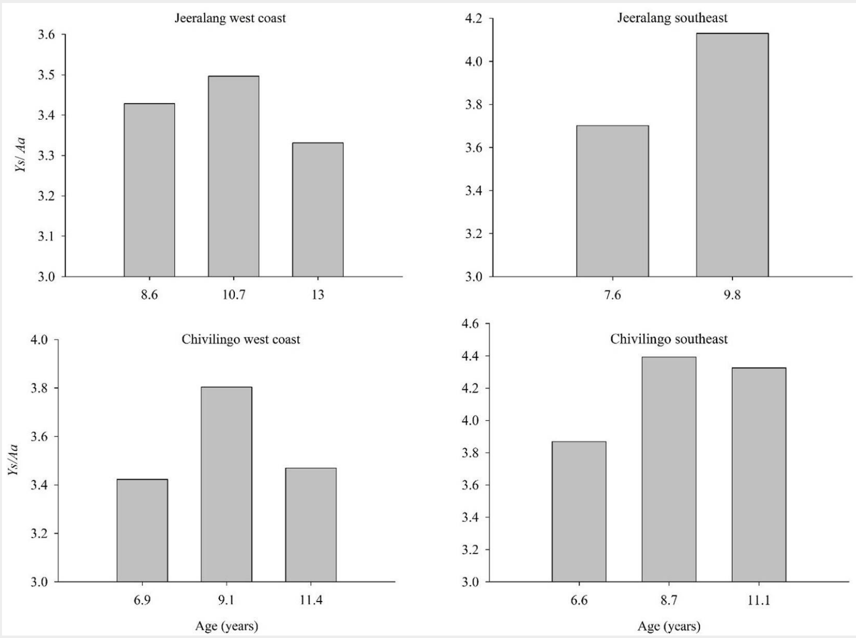
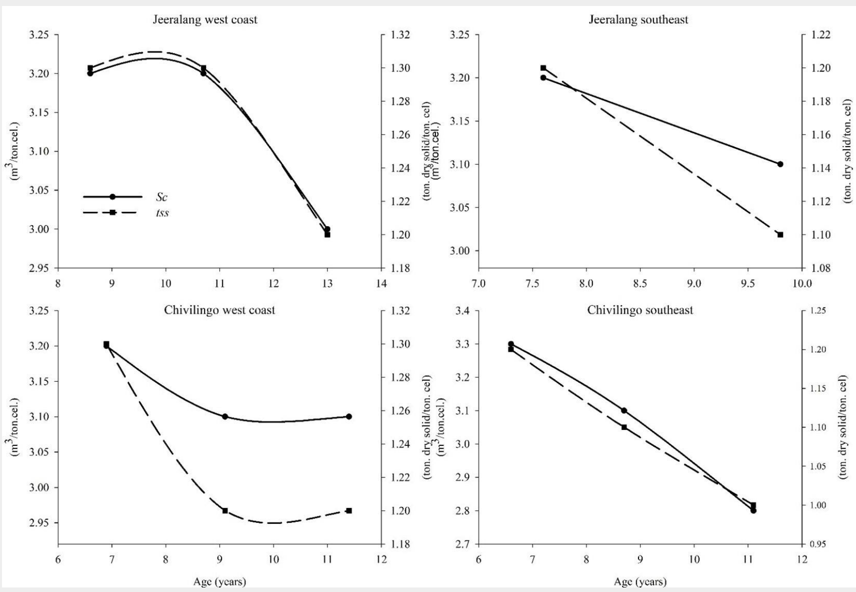


Fig. 4 - *Sc* and *tss* for the two seed origins and sites for the series of studied harvest ages.



Tab. 3 - Partial correlation values of two sets of variables: *Sc, Ys,* and *Wdpond* versus *Ch, Vh,* and *Wdpond.*

Comparison	r	p-value
Sc Ys vs. Wdpond	-0.94	<0.0001
Sc Wd pond vs. Ys	-0.96	<0.0001
Ch Ys vs. Vh Wdpond	0	0.99
Ch Vh vs. YsWdpond	0.89	0.01
Ch Wdpond vs. Vh Wdpond	0.05	0.91

Ch values with harvest age in the SE than in the SW (Fig. 1b). Chivilingo trees got an intersection of both curves around 8.5 years in the SW, while in the SEt a next age to 10 years and even higher for cellulose productivity per hectare. The largest increases in *Vh, Wh,* and *Ch* obtained with the increase in harvest age were registered with the Chivilingo origin in the SEsite with values of 55, 64, and 73%, respectively for the mentioned age range.

Pulping parameters

A significant increase in *Wdpond* with stand aging was observed except for the Jeeralang provenance at the southeastern site (Fig. 2). At that site, only two harvest ages were before harvest. Chivilingo seed source in the southeastern site showed the greatest increase in *Wdpond* (15%), which was close to double that obtained by the other plots, despite the fact that the difference in the range of ages evaluated was 4.5 years. However, Jeeralang plot in the SEt was an exception. The changes recorded for Y_s showed a trend similar to *Wdpond* except for Chivilingo origin at the SW site, where oscillations of values were observed at different ages. The largest Y_s was from the Chivilingo provenance, but the differences was small (only 5%).

The *Ys/Aa* ratio describes higher delignification of the wood per unit of reagent used for intermediate ages in all cases (Fig. 3). In general, these levels occurred between 9 and 11 years, with the highest values obtained at the SE site. The increase of *Ys* and *Wdpond* determined a decrease of *Sc* with the increase in harvest age in all cases (Fig. 4). The greater increases of these variables for the Chivilingo origin in the SE site explain the greater reduction in *Sc* (18%) with the increase in harvest age. The *tss* showed a similar trend to *Ys*, since the requirements of *Aa* remained relatively similar for all the ages evaluated.

The partial correlation coefficients calculated considering the four evaluated situations show a similar relative weight of *Wdpond* and *Ys* on *Sc* with very similar values for both variables (0.96 and 0.94, respec-

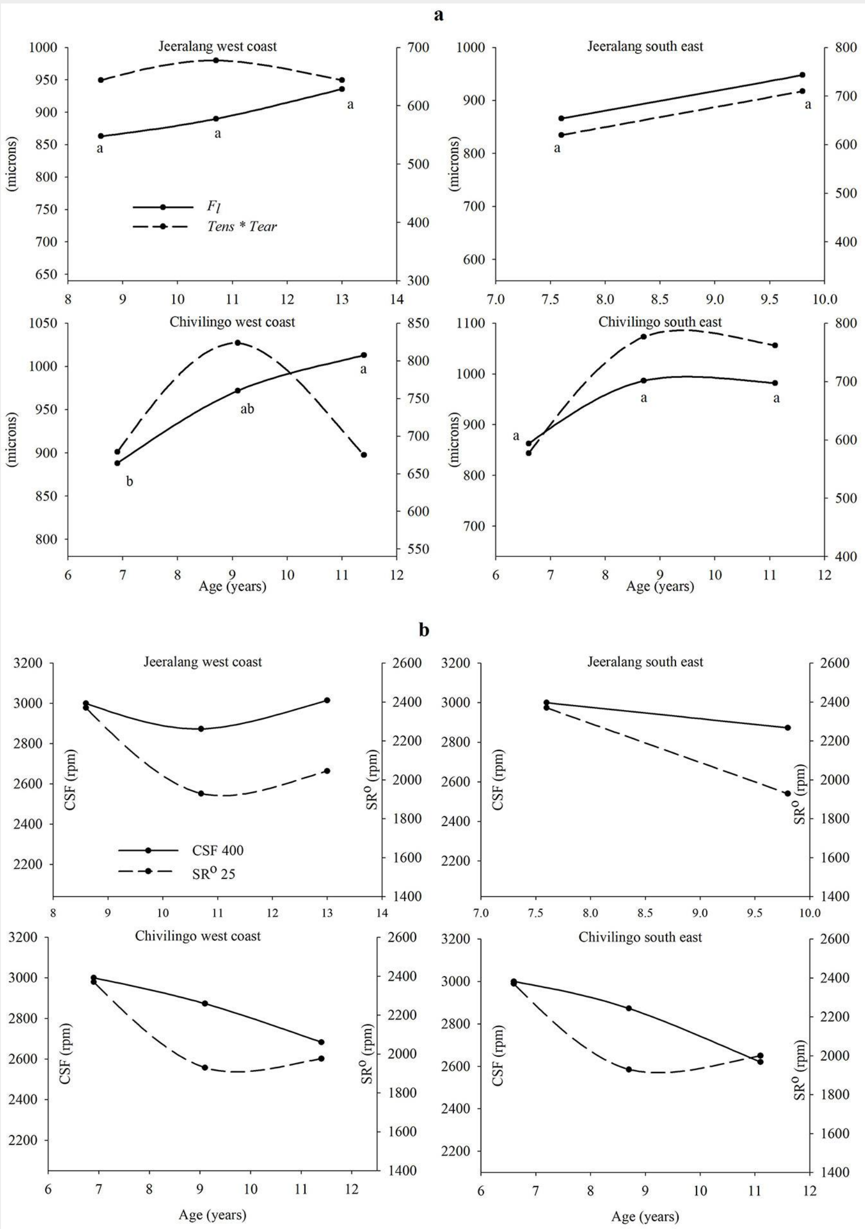


Fig. 5 - (a) *Fl* and *Tens·Tear* of cellulose sheets (at 25 *SR*°) for the two seed origins and sites for the series of studied harvest ages. (b) Refining requirements for two levels of drainability (25 *SR*° and 400 *CSF*) for the two seed origins and sites for the series of studied harvest ages (b).

Tab. 4 - Economic results for wood volume for the two seed origins and sites for the series of studied harvest ages. (*): estimated volume growth using the INIA model.

Seed origin	Sites	Age (years)	SEV (U$S ha^{-1})
Jeeralang	SW	8.6	7.501
		9.6 *	6.505
		10.7	5.585
		11.7 *	4.276
		13	4.653
	SE	7.6	6.195
		8.6 *	5.754
		9.8	4.794
		10.8 *	4.747
		11.8 *	4.273
		12.8 *	3.873
Chivilingo	SW	6.9	6.867
		7.9 *	5.083
		9.1	5.010
		10.2 *	4.438
		11.4	3.576
		12.4 *	2.824
	SE	6.6	6.353
		7.6 *	6.099
		8.7	5.699
		9.7 *	5.463
		11.1	5.557
		12.1 *	5.059
		13.1 *	4.508

Tab. 5 - Comparison of the effect of the rotation length on the set of variables analyzed for each seed origin and site. The values in parentheses express the relative changes observed (%) for each harvest age with respect to the previous one.

Seed origin	Sites	Age (years)	Vh (m^3ha^{-1})	SEV (U$S ha^{-1})	Ch (ton ha^{-1})	Ys (%)	Sc (m^3 ton^{-1})	Fl (µm)	Tens·Tear
Jeeralang	SW	8.6	266	7.501	70.2	50.4	3.2	863	644
		10.7	(4%)	(-26%)	(5%)	(1%)	(0%)	(3%)	(5%)
		13	(9%)	(-17%)	(13%)	(1%)	(-6%)	(5%)	(-5%)
	SE	7.6	203	6.195	56.8	52.2	3.2	866	620
		9.8	(12%)	(-23%)	(17%)	(4%)	(-3%)	(9%)	(15%)
Chivilingo	SW	6.9	171	6.867	48	51	3.2	888	679
		9.1	(7%)	(-27%)	(11%)	(3%)	(-3%)	(9%)	(21%)
		11.4	(13%)	(-29%)	(12%)	(-2%)	(0%)	(4%)	(18%)
	SE	6.6	178	6.353	48.8	53	3.3	863	577
		8.7	(23%)	(-10%)	(31%)	(4%)	(-6%)	(14%)	(35%)
		11.1	(26%)	(-2%)	(32%)	(2%)	(-10%)	(-1%)	(2%)

tively – Tab. 3). On the contrary, *Vh* had the greatest effect on *Ch* (0.89), while the effect of *Wdpond* and *Ys* was near to zero (0.053 and 0.0003, respectively).

Fiber length and paper properties of paper

The analysis of variance detected few changes in *Fl* with the increase of harvest age, except for the Chivilingo seeds at the SW site (Fig. 5a). The paper resistance showed similar relationship patterns to *Fl*. The refining requirements to reach the two levels of drainability (25 *SR*° and *CSF* 400) decreased with increasing harvest age (Fig. 5b). In all cases, more pronounced changes were observed in the *SR*° index than with the *CSF* for all harvest ages evaluated.

Forest value

Preliminary results showed that the highest *SEV* were reached at the youngest ages for the four sites. Therefore, a simulation of the volume per hectare was conducted to analyze the trend of the *SEV*. Results show that in all cases the highest forest value is associated to the smaller harvest age considered (Tab. 4). The Chivilingo SE site *SEV* results show the smallest difference between the youngest age and the following age, among the four sites considered (Tab. 5).

Discussion

Although the four plantations evaluated have aspects in common such as the origin of the seed, other characteristics such as soil type, stand age, and site preparation among others, are relatively different. Because the four plantations are not comparable to each other, they were evaluated independently, and the conclusions obtained are applicable to each case separately.

Our analysis confirms the hypotheses that different rotation length impact on wood production and economic results. Harvest age also affects pulping parameters, which lead to changes in capacity to converting wood into cellulose, and therefore to modify industrial efficiency. The biological optimum considered as the point where the mean annual increment (*MAI*) intersects the current annual increment (*CAI*) was not assessed. Instead, the economic criteria was prioritized along with wood quality, considering profitability and access to demanding markets. The wood price paid to forest owners depends on parameters such as wood density and pulping yield. Understanding the technological quality of wood produced for a span of rotation lengths would allow to better understand the consequences of management decisions and assist considering the best options to maintain such high-value markets, and to achieve a higher production potential for Uruguayan growth conditions.

Production per hectare and individual production

The accumulated Volume per hectare (*Vh*), Weight per hectare (*Wh*), and Cellulose production per hectare (*Ch*) of the Jeeralang seed source at the SW and SE sites and of the Chivilingo seed source at the SW site showed an increasing trend with increasing of harvest age. However, the annual growth rates in these three cases decreased for the three mentioned variables. *MAI* reduction is explained by the reduction of survival rate observed in all cases. The highest survival rate achieved was at the SE sites due to a low incidence of bark cankers and regrowth in the stem, related to better adaptation of the species to this region with maritime influence and with moderate to low average annual temperatures. The lower average temperature (close to 17 °C) at the SE site (Castaño et al. 2011) provided better growth conditions for the species than the rest of the forested areas in the country. The SW site had the lowest levels of reduction in survival (10%), which determined lower rates of *MAI* with the increase of harvest age lower than those recorded at SE sites. The reduction of the three variables mentioned was 19-29% for SW sites and 0-8% for SE sites. The largest and smallest relative increases were obtained with the Chivilingo seed source at the SE and SW, respectively. The performance of the Jeeralang provenance was more stable at both sites, as registered prior to the assessment (Resquin et al. 2012). The volume and gravimetric increase occurred at the same age in each of the three situations mentioned (8.5 to 10 years). A different result was observed for the Chivilingo seed origin planted in the SE site, because the increase of *Ch* productivity was later than *Vh* (> 11 *vs.* 10 years, respectively). Both types of results have been reported previously for eucalyptus species and were associated with changes in wood density and pulp yield as a function of the age of the trees (Resquin et al. 2019).

Pulping parameters

For all the plots, except for Jeeralang plot at the SE site, a significant increase in Wood density weighted (*Wdpond*) was observed from age 11 years. These changes occur in the dimensions of the wood cells and are associated with changes in the cambial meristematic tissue with increasing age. These changes generate juvenile wood in the first years of growth, depending on the species and generation of adult wood later. According to Foelkel (1978), in *Eucalyptus* species of 5-10 years old, the heartwood (consisting of juvenile wood) does not differ significantly from sapwood, with the sapwood frequently having a higher density than the heartwood. Foelkel (1978) points out that the formation of mature wood begins from 10 years of age, after which several of the technological properties tend to stabilize until an age close to 15 years old. The range of *Wdpond* recorded in the four situations was within the values reported in the literature for these origins (Resquin et al. 2006), although values are relatively high for this species. The observed increase of Yield screened (*Ys*) at all harvest ages (except for the Chivilingo plot in the SW) can be explained by the increase of *Wdpond*, because in denser woods there is greater availability of cell wall fibers from which cellulose can be extracted during the chemical pulping process. The thickness of wall fiber and its relationship with the lumen diameter greatly explain wood density (Carrillo et al. 2015). These ranges of *Wdpond* are not considered to limit the penetration and diffusion of the cooking liquor through the lumen and cell wall fibers (Silva 2011). This allows adequate impregnation with the liquor of the middle lamella, effective removal of lignin, and, consequently, a high yield of cellulose (Foelkel 2009a). This was confirmed by the increases of *Ys* values obtained with the Jeeralang and Chivilingo provenances at the SW and SE sites which reached the highest *Wdpond* values (0.580 gr cm^3) at 13 and 11 years old, respectively. Gomide et al. (2005) and Magaton et al. (2009) pointed out that pulping performance, besides being affected by the wood density, is linked to the content and composition of lignin, hemicellulose, extractive, and acid hexanuronic content. According to these authors, it is common to obtain an inversely proportional relationship between pulp yield and lignin and extractives content, because it is necessary to use harder cooking conditions (high charge of alkali, temperature, or reaction time) to remove these compounds. Some of these compounds, such as lignin and extractives, change with age, which helps to explain the increase in pulp yield with greater harvest age (Xie et al. 2000). The composition of lignin has also been shown to affect yield since the syringyl component (S) has greater reactivity against the alkali of the liquor and therefore, it is easier to remove than the guaiacyl component (G – Río et al. 2005). The fastest removal of lignin limits the loss of polysaccharides (cellulose and hemicelluloses) and facilitates the bleaching with a similar kappa index (Bassa 2002). The S/G ratio has been determined to increase with age in *E. globulus* (Rencoret et al. 2011), and in other eucalyptus species although at a younger age than that studied in this research (Morais et al. 2017). The extractives also have a negative relationship with cellulose yield at the studied harvest age, which can be problematic because of the pitch formation (Magaton et al. 2009). A third parameter that could increase *Ys* with age is the hemicellulose content (Rencoret et al. 2011), which favors the formation of hexanuronic acids during Kraft pulping (Magaton et al. 2009).

Based on the *Ys*/*Aa* relationship, the Chivilingo seed origin had low reagent cooking requirements close to 9 years at both studied sites. In the Jeeralang seed origin, this occurred around 11 years old, although in the SE site there was an increasing trend of these variables up to 10 years. Despite the fact that in all cases with higher harvest ages, a higher *Ys* and a lower Specific consumption (*Sc*) were obtained from the pulping in that age range, a higher efficiency of the applied Alkali active (*Aa*) charge was obtained in the removal of the lignin and extractives. The possible positive effect of the *Wdpond* on the *Aa* requirements was only detected for the Jeeralang origin at the SW site, while an opposite trend was observed at the SEsite. On the other hand, Chivilingo provenance showed independence between the parameters, indicating that *Aa* requirements may be associated with other parameters of wood composition. This lack of association between the *Aa* and *Wdpond* was also reported by Doldán (2007), who did not detect any relationship between *Ya* and *Wdpond,* though the study included samples older than 9 years old.

The evolution of *Sc* reflects the increase in both *Wdpond* and *Ys* with harvest age. From the point of view of efficiency in the pulp mill, Chivilingo provenance had the lowest use of wood per ton of pulp produced (15%) with a harvest age of 11 years. This means that a pulp production plant with a capacity of 1 million tons per year could reduce its wood consumption by 500,000 m^3. In the two situations where three harvest ages were evaluated, a lower response of this variable was observed compared with the increase in harvest age (6% and 8%). This reduction caan be explained in similar proportions by the *Ys* and the *Wdpond*. This reduction is important because wood cost represents around 50% of the operating costs of a bleached pulp mill (Dieste et al. 2018) and, at the same time, lower amounts of reagents are required with wood from young harvest trees. Additionally, it must be considered that a high *Ys*/*Aa* ratio creates a low amount of solids per ton of cellulose produced and, therefore, reduces the need to burn black liquor in the recovery boiler, which can be a limitation of the plant operation (Silva 2011). A low need for *Aa* would be an indicator of a low lignin content in the wood and would also contribute to a low generation of solids for the recovery process. In all situations, a reduction of solid content (*tss*) with the increase in harvest age was found, highlighting the Chivilingo seed source with a reduction of 17% with a harvest age of 11 years due to the increase in *Ys*. In the rest of the situations, the level of reduction with the more advanced harvest ages was of low magnitude (around 8%) due to the low values of *Ys*. In contrast to the results of Bassa (2002), the positive relationship expected between *Aa* and *tss,* due to the removal of lignin, carbohydrates, and the reagent charge during the pulping (Silva Jr 1994), was not found.

Fiber length and paper properties

The evolution of Fiber length (*Fl*) indicated that there were no significant changes with increasing the harvest age. The *Fl* values for the four evaluated situations were relatively similar. This stability in the values is an indication that the four plots were transitioning towards the formation of adult wood, where the fiber dimensions will remain with few age-related changes (Tomazello Filho 1987). The *Fl* is one of the most frequently used parameters to determine the formation of these types of woods in eucalyptus, although the wood density profile and microfibrillar angle have also been used (Souza et al. 2017). Doldán (2003) and Leonello et al. (2008) consider the use of the position in the radius (pith-bark sense) more useful to define the position of the three types of wood (juvenile, transition, and adult). Results obtained with *E. grandis* indicate that the transition age from juvenile to adult wood occurs between 6 and 8 years, although this largely depends on the growth rate (Palermo et al. 2015, Trevisan et al. 2017). Doldán (2003) evaluated 18-year-old *E. grandis* and identified the transition from juvenile to adult wood in approximately 50% by the position in the pith-bark direction, which represents around 25% of the stem wood. Similar results regarding the position in the radius of the change of the wood type in this species have also been reported (Leonello et al. 2008, Palermo et al. 2015, Trevisan et al. 2017).

The length and thickness of the wall fiber together with wood density were among the factors that had the greatest impact on the type and characteristics of the produced paper (Foelkel 2009b). Generally, the *Fl* is a variable positively linked to resistance to tearing and the refinability of the pulp (Souza et al. 2017) and indirectly linked to fiber population and coarseness, which largely determine the type of paper obtained (Foelkel 2007). Our results showed a trend to increase *Fl*, which would explain the positive response of paper resistance with two seeds origins planted in the southeast, as it increased at harvest age. According to Barrichelo & Brito (1976), the longest fibers in eucalyptus trees favor their union during the refining process, which leads to the formation of more compact and sheet resistant pulp, which is favored by the high content of hemicelluloses characteristic of *E. globulus* (Bassa 2006). The greatest increase in the resistance index was obtained with the Chivilingo trees in the SE site (35%) by increasing the harvest age from 6.6 to 8.7 years, despite the fact that at the age of 11.1 years a similar resistance level was shown. The increase in resistance index is also explained by the increase of *Wdpond* that occurred with the increase of harvest age, for the same drainability value. However, the Jeeralang seed source had few changes in sheet resistance at the different harvest ages at both sites, although the changes of *Fl* were of a similar magnitude to those registered with the Chivilingo provenance. However, in all cases, except with the Jeeralang provenance in the SW, we observed a decrease in refining requirements associated with the changes registered in the *FI* and eventually an increase in the content of hemicelluloses with age in the more advanced harvest (Rencoret et al. 2011).

Forest value

The best economic results at early harvest ages were explained by the growth curve of the forest, since the price of wood was unique for the entire rotation. Therefore, it is possible to increase income by using crops that can be harvested at an early age, which is always convenient.

These results are in contrast with the harvest ages observed in the region, where harvest age is 10-12 years. This suggests that there are opportunities to extend the harvest age and obtain a better economic results. However, these results are subject to variations in expected returns, which can vary by site; in Uruguay, productivity is very different between regions and sites. Additionally, it is important to note that the quality of the pulpwood was not included in this analysis. Different prices for wood within the industry may have affected the economic results obtained. Such an analysis was not possible given the complexity of the processes involved from an industrial point of view. In Uruguay, prices are not currently paid based on the performance of the pulpmill. However, there are differential payments for some species with better performing pulpwood and improved paper properties.

Identification of the best harvest time

Analysis of the optimum harvest age among the alternatives analyzed must be carried out considering the agrarian and industrial phase and recognizing that an integration does not always occur in forest enterprises (Tab. 5). Therefore, the best harvest option is likely to be a balance of the efficiency of the different stages of the production chain. From the point of view of *Vh,* the growth rates per unit of time with the Jeeralang provenance at earlier ages were higher in the SE than in the SW sites, while the opposite was observed with the Chivilingo seed source. Considering the *Ch*, among the alternative harvest ages considered, the best harvest age with the Jeeralang provenance occurs at 10-13 years in the SW sites and 8.5-10 years in the SE sites. On the other hand, the best harvest age for Chivilingo seed source was 9-11 years in the SE sites and at somewhat lower ages in the SW sites. Considering the *Sc* and *tss*, the results show that better results could be obtained with longer harvest ages than those evaluated in this study. From the point of view of economic income of wood sale, the best results occur in the shortest rotation length in all studied cases.

Conclusions

The performances of the two seed sources of *E. globulus* at each of the sites showed that harvest age has an impact on both the production of wood and cellulose per hectare and on the pulp properties of the wood. In a range of differences in harvest ages close to 4 years, different results were obtained in all the parameters evaluated, except for fiber length and the resistance properties of the paper. At the farm level, short harvest ages allowed the best economic results. Currently, the harvest age used commercially in the SE zone (11 years) with the Chivilingo provenance allows high pulp yields per hectare and low wood consumption for the pulp mill, but is relatively extended considering only the production of wood per hectare. With the Jeeralang seed source, better results would be obtained for all the evaluated aspects (except in the consumption of wood and the generation of solids in liquor) using lower harvest ages. From an economic point of view, there is an opportunity to include a wood price adjustment for pulp yield, which could be of interest to the forest producer and the industry.

Acknowledgments

The authors thank the LATU and INIA institutions for the support provided for the execution of the project and the Montes del Plata and Cambium companies for allowing access to the forests in which the evaluations and samplings were carried out.

References

Alencar GSB (2002). Produção de celulose relacionada a precocidade na seleção de um hibrido *Eucalyptus grandis × Eucalyptus urophylla* [Study of wood quality for the cellulose production related to the precocity of a *Eucalyptus grandis × Eucalyptus urophylla* hybrid selection]. Universidade de São Paulo, Escola Superior de Agricultura "Luiz de Queiroz", Piracicaba, São Paulo, Brasil, pp. 88. [in Portuguese] [online] URL: http://www.teses.usp.br/teses/disponiveis/11/11150/tde-20190821-132709/publico/AlencarGlauciaSoaresBarbosa.pdf

Barrichelo LEG, Brito JO (1976). A madeira das espécies de Eucalipto como matéria prima para a industria de celulose e papel [Wood from eucalypts species as raw material for the pulp and paper industry]. Serie Divulgaçao PRODEPEF no. 13, Projeto de Desenvolvimento e Pesquisa Florestal, Brasília, DF, Brazil, pp. 145. [in Portuguese]

Bassa A (2002). Processos de polpação kraft convencional e modificado com madeiras de E. grandis e híbrido (*E. grandis × E. urophylla*) [Conventional and modified pulping process of Eucvalyptus grandis and hybrid (*Eucalyptus grandis × Eucalyptus urophylla*)]. Universidade de São Paulo, Escola Superior de Agricultura "Luiz de Queiroz", Piracicaba, São Paulo, Brasil, pp. 120. [in Portuguese] [online] URL: https://www.teses.usp.br/teses/disponiveis/11/11149/tde-20191218-123106/publico/BassaAlexandre.pdf

Bassa AGMC (2006). Misturas de madeira de *Eucalyptus grandis × Eucalyptus urophylla, Eucalyptus globulus* e *Pinus taeda* para produção de celulose kraft através do processo lo-solids® [Mixture of *Eucalyptus grandis × Eucalyptus urophylla, Eucalyptus globulus* and *Pinus taeda* wood chips for the production of Kraft pulp through Lo-Solids® process]. Universidade de São Paulo, Escola Superior de Agricultura "Luiz de Queiroz", Piracicaba, São Paulo, Brasil, pp. 170. [in Portuguese] [online] URL: http://www.teses.usp.br/teses/disponiveis/11/11150/tde-08032007-162226/publico/AnaBassa.pdf

Carrillo I, Aguayo MG, Valenzuela S, Elissetche JP (2015). Variations in wood anatomy and fiber biometry of *Eucalyptus globulus* genotypes. Wood Research 60 (1): 1-10.

Castaño JP, Ceroni A, Furest M, Aunchayna J, Bidegain R (2011). Caracterización agroclimática del Uruguay 1980-2009. [Agroclimatic Characterization of Uruguay 1980-2009]. Serie Técnica INIA 193: 33. pp. 40. [in Spanish] [online] URL: http://www.ainfo.inia.uy/digital/bitstream/item/2538/1/18429021211104157.pdf

Dieste A, Baño V, Cabrera MN, Clavijo L, Palombo V, Moltini G, Casella F (2018). Forest-based bioeconomy areas. Strategic products from a technological point of view. Universidad de la República, Facultad de Ingeniería, Montevideo, Uruguay, pp. 64.

Dieste A, Cabrera MN, Clavijo L, Cassella N (2019). Analysis of wood products from an added value perspective: the Uruguayan forestry case. Maderas: Ciencia y Tecnologia 21 (3): 305-16. - doi: 10.4067/S0718-221X2019005000303

Doldán J (2003). Indicadores de calidad de madera *Eucalyptus grandis* de Río Negro, Uruguay. Contenido de humedad, densidad, contracción y largo de fibras [Wood quality indicators *Eucalyptus grandis* from Río Negro, Uruguay. Moisture content, density, shrinkage and fiber length]. Proyecto de Productos Forestales Tecnología de Ensayo LATU-JICA (1998-2003), 2003. Informe de Investigación no 9, Publicaciones LATU, Montevideo, Uruguay, pp. 42.

Doldán J (2007). Evaluación de parámetros de calidad de *Eucalyptus globulus* y *Eucalyptus maidenii* de plantaciones uruguayas para pulpa de celulosa [Evaluation of quality parameters of *Eucalyptus globulus* and *Eucalyptus maidenii* from Uruguayan plantations for cellulose pulp]. Nota Técnica no. 8, Publicaciones LATU, Montevideo, Uruguay, pp. 8.

Foelkel CEB (1978). Madeira do eucalipto: da floresta ao digestor [Eucalypt wood: from the forest to the digester]. In: "I Congresso Brasileiro Sobre a Qualidade da Madeira. Promoção IPEF - ABCP, XI Congresso Anual Da ABCP". São Paulo (Brazil) 22-25 Nov 1978. Boletim Informativo IPEF, Piracicaba, Brazil, vol. 6, pp. E1-E25. [in Portuguese]

Foelkel CEB (2007). As fibras dos eucaliptos e as qualidades requeridas na celulose kraft para a fabricação de papel [Eucalypt's fibers and the qualities required in kraft pulp for paper production]. Eucalyptos Online Book and Newsletter, ABTCP - Associação Brasileira Técnica de Celulose e Papel, pp. 48. [in Portuguese] [online] URL: http://www.eucalyptus.com.br/capitulos/PT03_fibras.pdf

Foelkel CEB (2009a). Propriedades papeleiras das Árvores, madeiras e fibras celulósicas dos eucaliptos [Paper properties of eucalypts trees, wood and cellulosic fibers]. Eucalyptus Online Book and Newsletter, ABTCP - Associação Brasileira Técnica de Celulose e Papel, pp. 111. [in

Portuguese] [online] URL: https://www.eucalyptus.com.br/eucaliptos/PT14_PropPapeleiras.pdf
Foelkel CEB (2009b). Individualização das fibras da madeira do eucalipto para a produção de celulose kraft [Individualization of eucalypts wood fibers for kraft cellulose production]. Eucalyptos Online Book and Newsletter, ABTCP - Associação Brasileira Técnica de Celulose e Papel, pp. 108. [in Portuguese] [online] URL: http://www.if.ufrrj.br/biolig/art_citados/IndividualizaçãodasfibrasdamadeiradoEucaliptoparaaproduçãodeceluloseKraft.pdf
Gomide JL, Colodette JL, Oliveira CR, Silva CM (2005). Caracterização tecnológica, para produção de celulose, da nova geração de clones de *Eucalyptus* do Brasil [Technological characterization of the new generation of *Eucalyptus* clones in Brazil for kraft pulp production]. Árvore 29 (1): 129-37.
Hirigoyen A, Franco J, Diéguez U (2018). Modelo dinámico de rodal para *Eucalyptus globulus* (L.) en Uruguay [Dynamic stand model for *Eucalyptus globulus* (L.) in Uruguay]. Agrociencia Uruguay 22 (1): 63-80.
ISO (2005). ISO 5269-1:2005: Pulps - Preparation of laboratory sheets for physical testing - Part 1: Conventional sheet-former method. Geneva, Switzerland, pp. 7.
ISO (2002). ISO 5264-2:2002: Pulps - Laboratory beating - Part 2: PFI mill method. Geneva, Switzerland, pp. 16.
ISO (1998). ISO 5270:1998: Pulps - Laboratory sheets -Determination of physical properties. Geneva, Switzerland, 8p.
Kibblewhite RP, Johnson BI, Shelbourne CJA (2001). Kraft pulp qualities of *Eucalyptus nitens, E. globulus*, and *E. maidenii*, at ages 8 and 11 years. New Zealand Forest Research Institute 30 (3): 447-57.
Kottek M, Grieser J, Beck C, Rudolf B, Rubel F (2006). World map of the Köppen-Geiger climate classification updated. Meteorologische Zeitschrift 15 (3): 259-63. - doi: 10.1127/0941-2948/2006/0130
Leonello EC, Palma HAL, Ballarin AW (2008). Delimitação da madeira juvenil e adulta de Eucalyptus grandis em São Paulo, Brasil [Juvenile-mature wood demarcation in *Eucalyptus grandis* in São Paulo, Brasil]. Revista Forestal Venezolana 52 (1): 93-98. [in Portuguese]
Lopes ED, Laia ML, Dos Santos AS, Soares GM, Leite RWP, Martins NS (2017). Influência do espaçamento de plantio na produção energética de clones de *Corymbia* e *Eucalyptus* [Influence of planting spacing on energy production of *Corymbia* and *Eucalyptus* clones]. Floresta 47 (1): 95-104. [in Portuguese] - doi: 10.5380/rf.v47i1.47141
Magaton ADA, Colodette JL, Gouvêa ADFG, Gomide JL, Muguet MCDS, Pedrazzi C (2009). Eucalyptus wood quality and its impact on kraft pulp production and use. Tappi Journal (Aug 2009): 32-40.
Megown KA, Turner P, Male JR, Retief JR (2000). The impact of site index and age on the wood, pulp and pulping properties of a *Eucalyptus grandis* clone (Tag 5). In: Proceedings of the IUFRO Conference "Forest Genetics for the Next Millennium". Durban (South Africa) 8-13 Oct 2000, pp. 169-173.
MGAP/DIEA (2020). Anuario Estadístico Agropecuario [Agricultural statistical yearbook]. Montevideo, Uruguay, pp. 270. [in Spanish]
Miranda I, Pereira H (2002). Variation of pulpwood quality with provenances and site in *Eucalyptus globulus*. Annals of Forest Science 59: 283-291. - doi: 10.1051/forest:2002024
Mokfienski A, Colodette JL, Gomide JL, Carvalho AML (2008). Relative importance of wood density and carbohydrate content on pulping yield and product quality. Ciência Florestal 18 (3): 401-413.
Morais PHD (2008). Efeito da idade da madeira de eucalipto na sua química e polpabilidade, e branqueabilidade e propriedades fisicas da polpa [Effect of age of the wood of eucalypt in its chemical and pulpability, and bleachability and properties of the pulp]. Universidade Federal de Viçosa, Minas Gerais, Brasil, pp. 79. [in Portuguese] [online] URL: https://www.locus.ufv.br/bitstream/123456789/2085/1/textocompleto.pdf
Morais PHD, Longue Junior D, Colodette JL, Morais EHC, Jardim CM (2017). Influence of clone harvesting age of *Eucalyptus grandis* and hybrids of *Eucalyptus grandis* × *Eucalyptus urophylla* in the wood chemical composition and in kraft pulpability. Ciência Florestal 27 (1): 237-248.
Palermo GPM, Latorraca JVF, De Carvalho AM, Calonego FW, Severo ETD (2015). Anatomical properties of *Eucalyptus grandis* wood and transition age between the juvenile and mature woods. European Journal of Wood and Wood Products 73 (6): 775-780. - doi: 10.1007/s00107-015-0947-4
R Core Team (2020). R: a language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. [online] URL: https://www.r-project.org/
Reina L, Galetta A, Vinciguerra V, Resquin F (2014). The relationship between *Eucalyptus grandis* lignin structure and kraft pulping parameters. Journal of Analytical and Applied Pyrolysis 107: 284-288. - doi: 10.1016/j.jaap.2014.03.013
Rencoret J, Gutiérrez A, Nieto L, Jiménez-Barbero J, Faulds CB, Kim H, Ralph J, Martínez AT, Del Río JC (2011). Lignin composition and structure in young *versus* adult *Eucalyptus globulus* plants. Plant Physiology 155 (2): 667-682. - doi: 10.1104/pp.110.167254
Resquin F, Navarro-Cerrillo RM, Carrasco-Letelier L, Rachid-Casnati C (2019). Influence of contrasting stocking densities on the dynamics of above-ground biomass and wood density of *Eucalyptus benthamii, Eucalyptus dunnii*, and *Eucalyptus grandis* for bioenergy in Uruguay. Forest Ecology and Management 438: 63-74. - doi: 10.1016/j.foreco.2019.02.007
Resquin F, Barrichelo LEG, Da Silva Jr FG, Brito JO, Sansigolo CA (2006). Wood quality for kraft pulping of *Eucalyptus globulus* origins planted in Uruguay. Scientia Forestalis/Forest Sciences, no 72: 57-66.
Resquin F, Fariña I, Rachid C, Rava A, Doldán J (2012). Influencia de la edad de corte en el pulpeo de *Eucalyptus globulus* plantado en Uruguay [Influence of harvest age on kraft pulp production for *Eucalyptus globulus* planted in Uruguay]. Agrociencia Uruguay 16 (2): 27-38. [in Spanish]
Río JC, Gutiérrez A, Hernando M, Landín P, Romero J, Martínez AT (2005). Determining the influence of eucalypt lignin composition in paper pulp yield using Py-GC/MS. Journal of Analytical and Applied Pyrolysis 74: 110-115. - doi: 10.1016/j.jaap.2004.10.010
Santos MD (2011). Efeito do espaçamento de plantio na biomassa do fuste de um clone híbrido do interespecífico de *Eucalyptus grandis* e *Eucalyptus urophylla* [Effect of the plantation spacing in the stem biomass of a hybrid clone interspecific of *Eucalyptus grandis* and *Eucalyptus urophylla*]. Universidade Estadual Paulista "Júlio de Mesquita filho", Faculdade de Ciências Agronômicas, Campus de Botucatu, São Paulo, Brasil, pp. 152. [in Portuguese] [online] URL: http://repositorio.unesp.br/bitstream/handle/11449/99799/santos_md_me_botfca.pdf?sequence=1&isAllowed=y
Santos SR (2005). Influência da qualidade da madeira de híbridos de *Eucalyptus grandis* × *Eucalyptus urophylla* e do processo kraft de polpação na qualidade da polpa branqueada [Wood quality influence of *Eucalyptus grandis* × *Eucalyptus urophylla* hybrids and kraft pulping process in bleached pulp quality]. Universidade de São Paulo, Escola Superior de Agricultura "Luiz de Queiroz", Piracicaba, São Paulo, Brasil, pp. 178. [in Portuguese] [online] URL: http://pdfs.semanticscholar.org/1fcd/9e9781bde0d65f5bccb9bc3f7c4c3ef73f22.pdf
Silva Jr FG (1994). Conversão do processo kraft em soda DDA (Sal Disódico de 1,4-di-hidro-9-10-di-hidroxiantraceno) para madeira de Eucalipto [Conversion of the Kraft process in soda-DDA (Di-sodium salt of 1,4-dihydroxianthracene) for Eucalyptus]. Universidade de São Paulo, Escola Superior de Agricultura "Luiz de Queiroz", Piracicaba, São Paulo, Brasil, pp. 194. [in Portuguese] [online] URL: http://www.teses.usp.br/teses/disponiveis/11/11149/tde-20191218-142829/publico/SilvaJuniorFrancidesGomesDa.pdf
Silva MG (2011). Produtividade, idade e qualidade da madeira de eucalyptus destinada à produção de polpa celulósica branqueada [Productivity, age and wood quality of Eucalyptus for bleached pulp production]. Universidade de São Paulo, Escola Superior de Agricultura "Luiz de Queiroz", Piracicaba, São Paulo, Brasil, pp. 95. [in Portuguese] [online] URL: http://www.teses.usp.br/teses/disponiveis/11/11150/tde-17032011-162129/publico/Marileide_Gomes_da_Silva.pdf
Souza MT, Lima JT, Soares BCD, Goulart SL, Lima LC (2017). Statistical delimitation of juvenile and mature wood of *Eucalyptus* and *Corymbia*. Scientia Forestalis/Forest Sciences 45 (116): 611-618.
TAPPI (2006). Standard test methods. Technical Association of the Pulp and Paper Industry - TAPPI, Atlanta, GA, USA. [Cd-rom]
Tomazello Filho M (1987). Variação radial da densidade básica em estrutura anatômica da madeira do *Eucalyptus globulus, E. pellita* e *E. acmenioides* [Radial variation of wood density in anatomical structure of *Eucalyptus globulus, E. pellita* and *E. acmenioides* wood]. Ipef 36: 35-42. [in Portuguese]
Trevisan R, Rosa M, Haselein CR, Santini J, Gatto DA (2017). Dimensões das fibras e sua relação

com a idade de transição entre lenho juvenil e adulto de *Eucalyptus grandis* W. Hill Ex Maiden [Fiber dimensions and their relationship with the transition age between juvenile and mature wood of *Eucalyptus grandis* W. Hill ex Maiden]. Ciencia Florestal 27 (4): 1385-1393. [in Portuguese]

Villacura L (2012). Determinación de la edad de rotación óptima para dos variedades híbridas del género *Populus* ubicadas en el valle central de la Región Del Maule [Determination of the optimal rotation age for two hybrid varieties of the genus *Populus* Located in the central valley of the Maule Region]. Universidad Austral de Chile, Facultad de Ciencias Forestales, Valdivia, Chile, pp. 70. [in Spanish] [online] URL: http://cybertesis.uach.cl/tesis/uach/2012/fifv712d/doc/fifv712d.pdf

Xie Y, Wu H, Zeng Z, Lai Y (2000). Effect of wood age on the pulping characteristic and chemical composition of *Eucalyptus globulus*. Chemistry and Industry of Forest Products 20 (1): 21-26.

Supplementary Material

Tab. S1 - Main characteristics of the plots installed in the field.

Tab. S2 - Statistics of the parameters of each of the fitted models.

Fig. S1 - Graphical inspection of the model residuals of *Ht*, *Vi* and *Wi* for Jeeralang provenance at SW site.

Fig. S2 - Graphical inspection of the model residuals of *Wi*, *Ht*, and *Vi* for Jeeralang provenance at southwest site.

Fig. S3 - Graphical inspection of the model residuals of *Ht*, *Vi* and *Wi* for Chivilingo provenance at SW site.

Fig. S4 - Graphical inspection of the model residuals of *Ht*, *Vi* and *Wi* for Chivilingo provenance at SE site.

Tab. S3 - Main characteristics of the ECF bleaching stages.

Tab. S4 - Cost values of forestry operations and wood prices.

Link: Resquin_4040@suppl001.pdf