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

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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 (Magan 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 (Magan et al. 2009, Kibblewhite et al. 2001). These transformations are associated with the change that occurs as the tree grows from 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-

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sumption, and an improvement in the resis-
tance 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 ex-
pected an increase in the wood density with age, within certain age ranges, lead-
ing to an increase in the pulp yield. How-
ever, opposite results have also been re-
ported (Miranda & Pereira 2002). Addition-
ally, an excessive wood density could ham-
per chip flow 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 (Mok-
fienksi et al. 2008). High values of wood density consume more energy during chipp-
ing, 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 thick-
ness of the fibers (associated with the in-
crease 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 pro-
duce sanitary papers, which require high specific volume. It has also been identified that the high positive correlation between wood age and holocellulose content is ac-
panied by a negative correlation be-
 tween wood age and the extractives and lignin affecting cellulose yield (Xie et al. 2000, Goimide et al. 2005). The removal of both lignin and extractives requires alkali consumption or determine hard kraft pulping condi-
tions, which could promote the degradation of the more hydrolysable cel-
lulose and essential hemicelluloses and in-
crease the solids content of the cooking liquor (Silva 2011). 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) deter-
mined 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, con-
tent of solids in liquor, refining require-
ments), and in the characteristics of the pa-
per obtained. To define the best harvest age for forest production, it is important to con-
sider 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 (Diestel et al. 2019). Therefore, to mini-
mize the net benefits of cellulose pulp pro-
duction (i.e., wood production and indus-
trial conversion), a key goal is to choose the best harvest age for forest plantation. It was hypothesized that rotation age af-
fects the properties of the wood produced, pulp and paper production, and the eco-
nomic value of the forest. To test this hy-
pothesis, this study: (i) estimated the tim-
eous values of E. globulus at different harvest ages in southeast and southwest Uruguay with two origins of commercial seed; (ii) identified the har-
est ages with high pulp yield per hectare and low wood consumption; and (iii) esti-
imated the economic results of the planta-
tions at each rotation age for each situa-
tion. The information obtained in this work allows to optimize the harvest age consid-
ering all the aspects of the forestry-indus-
trial value chain. This information can be

used by forestry producers in different coun-
try regions to choose the rotation length with the the best economic result, considering the growth and the price ob-
tained for the wood based on its pulpable properties. This study reflects the prevail-
ing 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 Aguilas company in the VIII re-

gion of Chile) on two forest soils of the southwest (SW) and southeast (SE) re-

gions 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 50 trees (aver-

age) and 30 rows of 46 trees for Chivilingo/Jeeralang on the SW and Chivilingo/Jeer-
alang 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 representa-

tive 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 (Cas-
taño et al. 2011). The climate is subtropical temperate without dry season (Cfa), ac-

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 evalu-
ate the effect of the harvest age with two seed sources in two forest regions. A sys-

tematic 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 pe-

period of one week considering an age range from 6.6 to 13 years.

Tree sampling and growth measurement

In the aforementioned years the diame-
ter at breast height (DBH, cm) was mea-
sured with a diameter tape in all trees, but total height (Ht, m) was measured in ap-
proximately 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 penetra-
tion 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 ex-

tracted for laboratory analysis. The number of felled trees within the groups with high, medium and low values of Pilodyn penetra-
tion was in proportion to the Basal Area (BA, m²) that each of the classes represents in the total BA of the plot. Each tree from each 15-tree group was measured for diam-
eter with and without bark at the base, at 0.7 m, 1.3 m, and then every 1 m up to com-
cernal height (Hc, m) (diameter of 6 cm with bark). This data was used to calculate the individual volume (V, m³) using the Smalian’s formula, which was later used to ad-
just 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, to determine the weighted basic density of each tree (Wdpound, g cm³). The Wdpound of each tree was estimated according to eqn. 1 (Santos 2011):

\[ \text{Wdpound} = \frac{A_5 \times W_5 + A_{50} \times W_{50} + A_{75} \times W_{75}}{A_5 + A_{50} + A_{75}} \]  

(1)

where Wdpound 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 indi-

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individual stem (Wi, kg) was calculated as the product of Vi (converted to cm³) 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 (FI, μm) according to the TAPPI (2006). To measure the FI 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 FI 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 (%), and KI were in accordance with the TAPPI (2006). With the values obtained the Specific consumption (Sc, m³ cel ton⁻¹) and Solid content (tss, %) were estimated as follows (eqn. 2, eqn. 3):

\[
Sc = \frac{1}{\text{Wdpond} \times Ys} \\
tss \times \text{odt} = \left(\frac{100 - Yt + Aa}{Ys}\right)
\]

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: 6, 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 m² 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 398, 2869, 2971, and 3819 data for plots Jeeralang 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 R², 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, m³), Weight per hectare (Wh, ton) and Medium Annual Increment of volume and weight (MAI, m³ ha⁻¹ year⁻¹ and ton ha⁻¹ 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):

\[
SEV = \frac{NPV \times (1+i)^n}{(1+i)^m-1}
\]

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

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

<table>
<thead>
<tr>
<th>Sites</th>
<th>Models</th>
<th>Parameter estimated</th>
<th>R² adjusted</th>
<th>RMSE</th>
<th>Bias</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jeeralang SW</td>
<td>1.3×(0.224280×1.273639/(DBH)⁻¹.31)</td>
<td>Ht</td>
<td>0.77</td>
<td>1.89</td>
<td>3.23×10⁻¹</td>
</tr>
<tr>
<td>Jeeralang SE</td>
<td>34.9163×exp(1.795/DBH)</td>
<td>Ht</td>
<td>0.73</td>
<td>1.58</td>
<td>-3.69×10⁻⁰</td>
</tr>
<tr>
<td>Chivilingo SW</td>
<td>DBH/(0.508279+0.025815×DBH)</td>
<td>Ht</td>
<td>0.59</td>
<td>2.07</td>
<td>1.49×10⁻⁰</td>
</tr>
<tr>
<td>Chivilingo SE</td>
<td>-11.8122+11.5313×ln(DBH)</td>
<td>Ht</td>
<td>0.74</td>
<td>2.06</td>
<td>-3.97×10⁻⁰</td>
</tr>
<tr>
<td>Jeeralang SW</td>
<td>exp(-10.6078+1.7462×ln(DBH)+1.3001×ln(Ht))</td>
<td>Vi</td>
<td>0.95</td>
<td>0.035</td>
<td>2.51×10⁻⁰</td>
</tr>
<tr>
<td>Jeeralang SE</td>
<td>3.5117×(1/DBH)×Ht⁻².81</td>
<td>Vi</td>
<td>0.99</td>
<td>0.011</td>
<td>-1.37×10⁻⁰</td>
</tr>
<tr>
<td>Chivilingo SW</td>
<td>2.249e⁻⁷×(DBH⁻¹.71)×(Ht⁻¹.16)</td>
<td>Vi</td>
<td>0.98</td>
<td>0.018</td>
<td>-1.66×10⁻⁰</td>
</tr>
<tr>
<td>Chivilingo SE</td>
<td>2.860e⁻⁷×(DBH⁻¹.08)×(Ht⁻¹.76)</td>
<td>Vi</td>
<td>0.98</td>
<td>0.024</td>
<td>-3.4×10⁻⁰</td>
</tr>
<tr>
<td>Jeeralang SW</td>
<td>exp(-5.6819+1.9072×ln(DBH)+1.5675×ln(Ht))</td>
<td>Wi</td>
<td>0.95</td>
<td>0.205</td>
<td>0.210</td>
</tr>
<tr>
<td>Jeeralang SE</td>
<td>exp(-4.39598+1.02825×ln(DBH)×Ht)</td>
<td>Wi</td>
<td>0.98</td>
<td>9.8</td>
<td>0.154</td>
</tr>
<tr>
<td>Chivilingo SW</td>
<td>0.010483×(DBH⁻¹.1071)×(Ht⁻¹.1256/16)</td>
<td>Wi</td>
<td>0.96</td>
<td>15.8</td>
<td>0.010</td>
</tr>
<tr>
<td>Chivilingo SE</td>
<td>exp(4.9493+1.0823×ln(DBH)×Ht)</td>
<td>Wi</td>
<td>0.97</td>
<td>18.4</td>
<td>0.060</td>
</tr>
</tbody>
</table>
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 (Wdp mond), 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 (F1), 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, Wdp mond and Ys and (ii) Ch, Wdp mond, Yh 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, 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

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

<table>
<thead>
<tr>
<th>Seed origin</th>
<th>Sites</th>
<th>Age (years)</th>
<th>DBH (cm)</th>
<th>Ht (m)</th>
<th>Vi (m³)</th>
<th>Survival (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jeeralang</td>
<td>SW</td>
<td>8.6</td>
<td>18.2</td>
<td>22.1</td>
<td>0.250</td>
<td>75</td>
</tr>
<tr>
<td></td>
<td></td>
<td>10.7</td>
<td>19.0</td>
<td>22.6</td>
<td>0.273</td>
<td>72</td>
</tr>
<tr>
<td></td>
<td></td>
<td>13.0</td>
<td>20.5</td>
<td>23.6</td>
<td>0.330</td>
<td>67</td>
</tr>
<tr>
<td></td>
<td>SE</td>
<td>7.6</td>
<td>16.3</td>
<td>19.2</td>
<td>0.167</td>
<td>86</td>
</tr>
<tr>
<td></td>
<td></td>
<td>9.8</td>
<td>17.2</td>
<td>19.9</td>
<td>0.194</td>
<td>84</td>
</tr>
<tr>
<td></td>
<td></td>
<td>6.9</td>
<td>19.3</td>
<td>18.6</td>
<td>0.214</td>
<td>67</td>
</tr>
<tr>
<td>Chivilingo</td>
<td>SW</td>
<td>9.1</td>
<td>20.0</td>
<td>19.2</td>
<td>0.239</td>
<td>66</td>
</tr>
<tr>
<td></td>
<td></td>
<td>11.4</td>
<td>21.8</td>
<td>20.4</td>
<td>0.302</td>
<td>60</td>
</tr>
<tr>
<td></td>
<td>SE</td>
<td>6.6</td>
<td>16.6</td>
<td>19.9</td>
<td>0.178</td>
<td>71</td>
</tr>
<tr>
<td></td>
<td></td>
<td>8.7</td>
<td>18.1</td>
<td>21.2</td>
<td>0.227</td>
<td>69</td>
</tr>
<tr>
<td></td>
<td></td>
<td>11.1</td>
<td>20.2</td>
<td>22.6</td>
<td>0.306</td>
<td>66</td>
</tr>
</tbody>
</table>

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**Fig. 1 - Accumulated values of Vh, Wh, and Ch, and the respective 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.
in the SW, while in the SE 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 SE site 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 SE was an exception. The changes recorded for Y 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 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 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, respectively). The differences was small (only 5%).

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, respectively). The differences was small (only 5%).

**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).

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

<table>
<thead>
<tr>
<th>Comparison</th>
<th>r</th>
<th>p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sc Ys vs. Wdpond</td>
<td>-0.94</td>
<td>&lt;0.0001</td>
</tr>
<tr>
<td>Sc Wdpond vs. Ys</td>
<td>-0.96</td>
<td>&lt;0.0001</td>
</tr>
<tr>
<td>Ch Ys vs. Wh Wdpond</td>
<td>0</td>
<td>0.99</td>
</tr>
<tr>
<td>Ch Wh vs. Ys Wdpond</td>
<td>0.89</td>
<td>0.01</td>
</tr>
<tr>
<td>Ch Wdpond vs. Wh Wdpond</td>
<td>0.05</td>
<td>0.91</td>
</tr>
</tbody>
</table>

**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.

<table>
<thead>
<tr>
<th>Seed origin</th>
<th>Sites</th>
<th>Age (years)</th>
<th>SEV (US$ ha⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SW</td>
<td>8.6</td>
<td>7.501</td>
<td></td>
</tr>
<tr>
<td></td>
<td>9.6</td>
<td>6.505</td>
<td></td>
</tr>
<tr>
<td></td>
<td>10.7</td>
<td>5.585</td>
<td></td>
</tr>
<tr>
<td></td>
<td>11.7</td>
<td>4.276</td>
<td></td>
</tr>
<tr>
<td></td>
<td>13</td>
<td>4.653</td>
<td></td>
</tr>
<tr>
<td>SE</td>
<td>7.6</td>
<td>6.195</td>
<td></td>
</tr>
<tr>
<td></td>
<td>8.6</td>
<td>5.754</td>
<td></td>
</tr>
<tr>
<td></td>
<td>9.8</td>
<td>4.794</td>
<td></td>
</tr>
<tr>
<td></td>
<td>10.8</td>
<td>4.747</td>
<td></td>
</tr>
<tr>
<td></td>
<td>11.8</td>
<td>4.273</td>
<td></td>
</tr>
<tr>
<td></td>
<td>12.8</td>
<td>3.873</td>
<td></td>
</tr>
<tr>
<td>SW</td>
<td>6.9</td>
<td>6.867</td>
<td></td>
</tr>
<tr>
<td></td>
<td>7.9</td>
<td>5.083</td>
<td></td>
</tr>
<tr>
<td></td>
<td>9.1</td>
<td>5.010</td>
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<td></td>
<td>10.2</td>
<td>4.438</td>
<td></td>
</tr>
<tr>
<td></td>
<td>11.4</td>
<td>3.576</td>
<td></td>
</tr>
<tr>
<td></td>
<td>12.4</td>
<td>2.824</td>
<td></td>
</tr>
<tr>
<td>SE</td>
<td>6.6</td>
<td>6.353</td>
<td></td>
</tr>
<tr>
<td></td>
<td>7.6</td>
<td>6.099</td>
<td></td>
</tr>
<tr>
<td></td>
<td>8.7</td>
<td>5.699</td>
<td></td>
</tr>
<tr>
<td></td>
<td>9.7</td>
<td>5.463</td>
<td></td>
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<tr>
<td></td>
<td>11.1</td>
<td>5.557</td>
<td></td>
</tr>
<tr>
<td></td>
<td>12.1</td>
<td>5.059</td>
<td></td>
</tr>
<tr>
<td></td>
<td>13.1</td>
<td>4.508</td>
<td></td>
</tr>
</tbody>
</table>
Impact of rotation length in Eucalyptus plantations

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.

<table>
<thead>
<tr>
<th>Seed origin</th>
<th>Sites</th>
<th>Age (years)</th>
<th>Vh (m³/ha)</th>
<th>SEV (US$ ha⁻¹)</th>
<th>Ch (ton ha⁻¹)</th>
<th>Ys (%)</th>
<th>Sc (m³/ton⁻¹)</th>
<th>FI (μm)</th>
<th>Tens-Year</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jeeralang</td>
<td>SW</td>
<td>8.6</td>
<td>266</td>
<td>7.501</td>
<td>70.2</td>
<td>50.4</td>
<td>3.2</td>
<td>863</td>
<td>644</td>
</tr>
<tr>
<td></td>
<td></td>
<td>10.7</td>
<td>(4%)</td>
<td>(-26%)</td>
<td>(5%)</td>
<td>(1%)</td>
<td>(0%)</td>
<td>(3%)</td>
<td>(5%)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>13</td>
<td>(9%)</td>
<td>(-17%)</td>
<td>(13%)</td>
<td>(1%)</td>
<td>(-6%)</td>
<td>(5%)</td>
<td>(-5%)</td>
</tr>
<tr>
<td></td>
<td>SE</td>
<td>7.6</td>
<td>203</td>
<td>6.195</td>
<td>56.8</td>
<td>52.2</td>
<td>3.2</td>
<td>866</td>
<td>620</td>
</tr>
<tr>
<td></td>
<td></td>
<td>9.8</td>
<td>(12%)</td>
<td>(-23%)</td>
<td>(17%)</td>
<td>(4%)</td>
<td>(-3%)</td>
<td>(9%)</td>
<td>(15%)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>6.9</td>
<td>171</td>
<td>6.867</td>
<td>48</td>
<td>51</td>
<td>3.2</td>
<td>888</td>
<td>679</td>
</tr>
<tr>
<td>Chivilingo</td>
<td>SW</td>
<td>9.1</td>
<td>(7%)</td>
<td>(-27%)</td>
<td>(11%)</td>
<td>(3%)</td>
<td>(-3%)</td>
<td>(9%)</td>
<td>(21%)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>11.4</td>
<td>(13%)</td>
<td>(-29%)</td>
<td>(12%)</td>
<td>(-2%)</td>
<td>(0%)</td>
<td>(4%)</td>
<td>(18%)</td>
</tr>
<tr>
<td></td>
<td>SE</td>
<td>6.6</td>
<td>178</td>
<td>6.353</td>
<td>48.8</td>
<td>53</td>
<td>3.3</td>
<td>863</td>
<td>577</td>
</tr>
<tr>
<td></td>
<td></td>
<td>8.7</td>
<td>(23%)</td>
<td>(-10%)</td>
<td>(31%)</td>
<td>(4%)</td>
<td>(-6%)</td>
<td>(14%)</td>
<td>(35%)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>11.1</td>
<td>(26%)</td>
<td>(-2%)</td>
<td>(32%)</td>
<td>(2%)</td>
<td>(-10%)</td>
<td>(-1%)</td>
<td>(2%)</td>
</tr>
</tbody>
</table>

Fiber length and paper properties of paper

The analysis of variance detected few changes in FI 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 FI. 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 Jeeralang 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. 2008), although values are relatively high for this species. The observed increase of Yield
Despite the fact that in all cases with both studied sites, the pitch formation (mentioned in the text) of hexanuronic acids during Kraft pulp extraction (which affects the yield since the syringyl component of lignin has also been shown to affect the increase in pulp yield with greater harvest age) was found, highlighting the Chivilingo provenance with a reduction of 17% by increasing their harvest age (11 years due to the increase of resistance index is also explained by the increase of wood density, 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) from the point of view of efficiency in the mill (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 of the bark, together with wood density, 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 (2005) 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 also showed independence between the pitch formation with two seeds origins planted in the southeast, as it increased at harvest age. According to Barrichello & 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 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 Jeerelang 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 Jeerelang origin at the SW site, while an opposite trend was observed at the SE site. On the other hand, Chivilingo provenance showed independence between the parameters, indicating that Aa requires a higher reagent charge, which is true for many 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 Ys and Wdpond, though the study included samples older than 9 years old.

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 of the bark, together with wood density, 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 (2005) 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).
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 return. 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 undefined 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
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Impact of rotation length in Eucalyptus plantations

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]


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 \( H_t \), \( V_i \) and \( W_i \) for Jeeralang provenance at SW site.

Fig. S2 - Graphical inspection of the model residuals of \( W_i \), \( H_t \), and \( V_i \) for Jeeralang provenance at southwest site.

Fig. S3 - Graphical inspection of the model residuals of \( H_t \), \( V_i \) and \( W_i \) for Chivilingo provenance at SW site.

Fig. S4 - Graphical inspection of the model residuals of \( H_t \), \( V_i \) and \( W_i \) 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