<u>Growth and economic analysis of a *Eucalyptus globulus* clonal spacing trial in Chile</u>

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ABSTRACT.

A *Eucalyptus globulus* clonal spacing trial teasting spacings from 500 to 3,000 stems per hectare for four clones was planted in Sept. 1994 on a deep volcanic-ash high productivity site near Mulchén, VIII Region, Chile, under a split-plot design with three replicates. The trial was measured at age 12 years and results across all clones and spacings were analysed from both, growth rate and economic perspective. A comparison with Permanent Sampling Plots [PSP] data from surrounding commercial seedlings plantations was also made.

Volume growth curves were simulated up to 16 years old for all treatments, and optimized Land Expectation Value [LEV = Faustmann Value] and rotation age were calculated for each combination of clone and stocking, and for the commercial stand. Cash flow values were calculated under current market costs and prices structure in Chile. Sensitivity analysis on mill gate pulpwood prices and plant prices was also carried out.

From the stocking perspective, the mean annual increment (MAI, in m^3 ha^{-1} y^{-1}) peaked at 1000 to 1500 sph with a value of 43.0 at 12 years age. From the clone perspective, the best clone reached an MAI of 44 at this stand density, while growth of the commercial stand was 40 at a current stocking of 1,400 sph. Non-significant statistical differences were found among three of the four clones tested. Overall survival was uniformly good, with a minimum value of 82% among clones across all initial densities, and it exceeded 92% for some spacings and clones. Overall survival of the trial was 95%, and no evidence of mortality due to competition was found, even at stockings as high as 3,000 sph.

Considering the best performing clone, optimal economic initial stocking was found at 1,500 sph. Under this scenario, optimal rotation age was found at age 9 years [LEV peak] at US$ 3,100 /ha;

commercial stand peaked at year 10 with a value of US$ 2,164 /ha. These differences, despite having non statistical significance, are relevant from a forest economics perspective.

Considering both biological and economics perspectives, it is concluded that harvesting age for clonal plantations would be 20% shorter than seedlings, with an initial stocking of 1,500 sph. and harvesting age of 9 years old. The yields and economic results found are very high, and should not be extrapolated to other sites or situations.

Key Words

Eucalyptus globulus; clonal; spacing trial; clonal breeding; growth curve; Land Expectation Value; cuttings.

1.- INTRODUCTION.-

In 1989 Forestal Mininco S.A. started its *Eucalyptus globulus* breeding programme aiming at increasing both growth rate and pulpwood quality for kraft processing plants.

The main traits defined were volume growth rate, basic density , pulp yield and as a secondary trait, frost tolerance.

The initial breeding population was split into three main origins: 350 families of local landrace from Colcura area [coastal range south from Concepción], 350 families from the natural distribution in Australia, and 250 additional selections from new commercial plantations of the company [Sanhueza. and Griffin 2001].

Progeny trials, clonal and seedlings seed orchards were planted. In 1991 a clonal propagation protocol was established as a parallel project, aimed to support a massive expansion as an operational practice. At this time, the propagation technology was successfully implemented at commercial scale and in 1994 the first clonal plantations were established.

Each year since then, a batch of more than 600 new clones has entered the testing program, with a first screening step on rooting. All those ranked higher than 50% on rooting go into the next stage in field test, which consist of two sequential tests for the main breeding objectives. The complete cycle takes 6 to 8 years to test a new genotype for commercial propagation.

Thus, every year a set of 5 to 8 new tested best clones are delivered to the nursery for commercial plantations, and displace a similar number of existing clones with lower rankings [Araujo et. al. 1997].

The current paper reports the growth performance of a 12.1 years old clonal spacing trial planted 1994 in a split-plot design with three replicates, with four of the first clones from phenotypic selections. In addition, an economic analysis was carried out across different stockings for the best performing genotype, and its economic value compared with data from permanent sampling plots established in the same stand, same age, but using commercial seedling stock with seed derived from a seed production area].

2.- AREA OF STUDY AND METHODOLOGY.

2.1.- Soil and Climate: the trial was planted in a farm located close to Mulchén town [37º 49' 44" S; 72º 15' 18" W], in a very deep volcanic ash soil [Andisol, > 2.5 m. depth] serie named Santa

Bárbara, commonly denominated “trumaos”. Previous land use was a rotation of annual crops, mainly wheat. Topography in this area is flat, with an elevation around 260 m.a.s.l.

This soil type is very productive, with high fertility and suitable for any intensive crop. Nutritional levels varies depending on the previous landuse. Normally organic matter content is around 8 to 19%, pH in water 5.2 to 5.9, P-Olsen 2 to 8 ppm., high organic P-fixation [Borie and Rubio, 2003], and K content from 60 to 250 ppm. Bulk density varies from 0.7 to 0.9 g cm^{-3}, with water holding capacity around 17 to 26% on volume.

Comment [har648 1]: Seems very high – are you sure?

Comment [har648 2]: This seems amazingly low – are you saying that this soil will float?)

The climate of the area is inland-influenced, with maximum temperatures in summer up to 38°C and frequent winter frosts down to -8°C. Total annual rainfall ranges from 1,300 to 1,800 mm, distributed mainly between April to December, with a dry season during January to March.
In summary, this is a very productive site for the most common forestry crops in Chile.

2.2.- Experimental Design: the trial was planted in September 1994, using a design that tested four ***E. globulus*** clones at six different stockings, ranging from 500 to 3,000 stems per ha. [increment of 500 sph each], all grouped in a split plot design with three replicates.
Each replicate has four randomized main plots, one per clone. Within plots, six stockings were allocated randomly to sub-plots, each one of them consisting of 48 measured plants, plus a buffer row [a total 80 plants per sub-plot]. Inter row distance was fixed at 3.5 m., and spacing within rows was varied to produce the target stockings.

2.3.- Clones: four different genotypes were considered in this trial, all of them untested phenotypic selections from progenies of plus trees. All these clones have now been out-ranked by subsequent clonal selections and are no longer deployed at commercial scale.

Clon X-2. was selected from the progeny of a plus tree from Colcura area. It was deployed up to 1997, when planting was discontinued because of windthrow risk at sites other than this trial. It showed excellent rooting performance.

Clones X-6, 7 and 8 were also derived form progenies of plus trees from Colcura area, and their planting has now been discontinued because rooting problems.

2.4.- Establishment practices: the trial was planted under the site-specific prescriptions used for commercial plantations at that period. In summary:

- Pre-planting weed control with 4 l ha^{-1} of glyphosate.
- Ripping to 25 cm. depth and fertilization with a blend of 210 g $tree^{-1}$. NPK-B placed along the rip line.
- Manual planting.
- Post-planting weed control in the first year, with a mixture of 3.5 l ha^{-1} of glyphosate and 4 l ha^{-1} of simazine.
- Second year fertilization with 50 g $tree^{-1}$, of boron [Ulexite].
- Second and third year springtime weed control. Same prescription as post-planting.

2.5.- Measurements, modeling and economic analysis: the trial was measured on height and DBH on 26th October 2006 at age 12.1. The database of results was processed for individual trees using an inventory processing system of the company. Mean values by plot were calculated [mean total height (TH), dominant height (DH), diameter at breast height (DBH), survival (S)], and aggregated on a per hectare basis. for variables basal area (BA) and standing volume [SV;s.u.b. up to 5 cm]. DH was defined as the average height of the 100 larger DBH trees per ha.

ANOVA tests were performed using SAS PROC GLM and SAS PROC MIX for main factors: clone and stocking. The Duncan test was performed for testing the significance of differences between clones.

The average results were compared with those from two circular permanent sampling plots [PSPs] located in the same stand but from a commercial plantation with the same age, site and establishment prescriptions, but using open-pollinated seedlings derived from a seed production area. The PSPs are part of the grid that the company established for long term growth monitoring. All these were located at random when the plantation was aged 3 years. Plot size of the PSPs is 400 m^2 and the trees are numbered and referenced by angle-distance coordinates.

Once average per-hectare values were calculated, statistical analysis was conducted on plot mean values to test significance of differences between clones, stockings and clone-by-stocking interactions.. A split-plot mixed model was used to compare differences between clones and initial stocking, where clone was considered as the whole plot and density as the split-plot. Both the clone and stocking were considered fixed effects and block a random effect.

A growth and yield simulation was carried out for variables DH, DBH, BA and SV. For each variable, new curves were obtained for ages 5 to 16. The system is based on incremental values of the variables in a compatible and interrelating system of growth and yield equations for predicting DH, DBH, BA, S and SV [Borders and Bailey, 1986; Cordero et. al. 2004]. The modeling data base came from 420 PSP distributed across different site conditions, species [mainly *E. globulus* and *E. nitens*] and annual measurements made during the last 15 years.

It must be noted that few PSP from the total used for modeling calibration include clonal plantation data. Then, there is some uncertainty in modeling accuracy for pure clone trials or plantations. To reduce the risk of reaching conclusions with large errors in the modeling output, comparisons were made using forward and backward validation, by projecting from real data at age 8.5 years modeled to age 12.1 years, and the real values from the measurement at age 12.1 projected back to age 8.5. No significant differences were found between these results.

The economic modeling was made only for the best performing clone, across all the different stockings. Land Expected Value [LEV] was considered as the valuation criterion, and its maximization [peak] along the growth curve as the optimal rotation age for each stocking treatment and for the commercial plantation [PSP data]. The land value is calculated as a residual value of the plantation’s discounted cash flow over an infinite rotations period at a given discount rate [LEV, or Faustmann Value, Faustmann, 1849; Chang, 1984; Gaffney, 1957; Leuschner, 1990].

The establishment costs come from real updated rates for commercial plantations in Chile, and include the extra nursery production cost for clonal plants versus seedlings. Similar criteria were applied for the costs of stocking treatments in all relevant activities involved, as well as the impacts on harvesting, roads, transportation and administration cost structure.

3.- RESULTS AND DISCUSSION.-

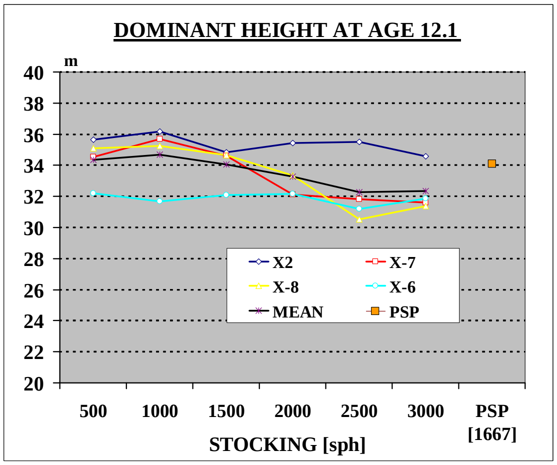
3.1.- Growth at age 12.1 years: no significant differences between treatments were found in survival, which simplifies comparisons for aggregated variables such as basal area and volume. Average survival of the trial was 95% which is excellent for a frost-prone site such as this.

Table 1 summarizes the ANOVA output for main variables analyzed:

TABLE 1: Significance of differences among clones, stockings and their interaction, determined from analysis of variance

		F-probability				
Source of Variation	Degrees of freedom	DBH	TH	DH	BA	Volume
Block	2	0.006	0.0166	0.001	<0.001	0.017
Clone	3	0.5689	0.0094	0.0215	0.6569	0.7609
Stocking	5	<0.001	<0.001	<0.0001	<0.001	<0.001
Clone * Stocking	15	0.4496	0.3663	0.043	0.3362	0.2708

Stocking had a highly significant ($P<0.001$) effect on all variates. There were significant differences between clones for TH and DH, but not for DBH, BA and volume. The interaction of stocking and clone was not significant for any of the variates. The best clone for standing volume and dominant height was clone X-2.



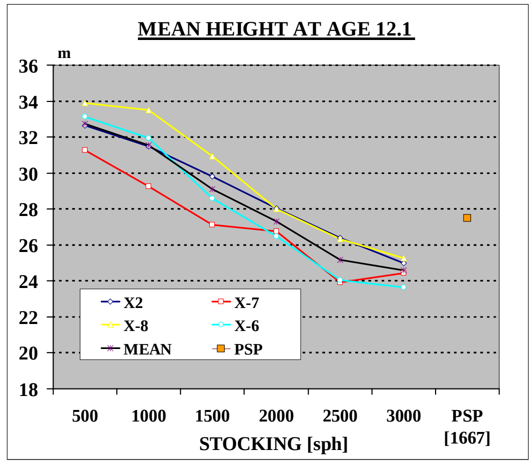


FIGURE 1: DH by clone and stocking

FIGURE 2: MH by clone and stocking.

As showed in Figure 1, DH of two clones [X-2 and X-6] changed little across initial spacing at age 12 years. The other two clones tended to decrease in their DH at spacings closer than 1,500 sph. The average of all clones was similar to the value for seedlings in the nearby commercial plantation [PSP]. The relationship between MH and spacing is quite different: all the clones showed a trend of reducing average height with closer spacing.

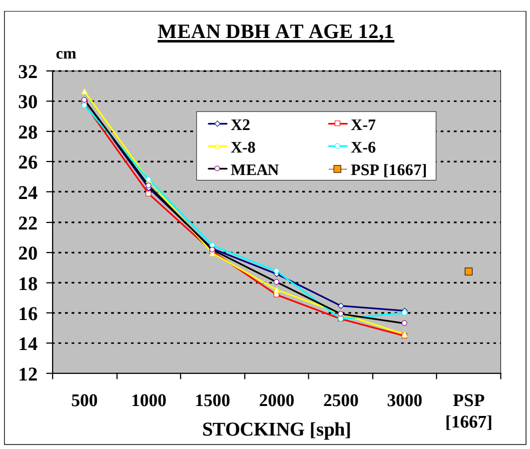


FIGURE 3: DBH by clone and stocking.

For DBH, the response of the different clones to initial spacing was more uniform than DH, showing the typical inverse relationship between DBH and stocking. All clones showed the same tolerance to competition up to 1,500 sph. Higher stocking showed differences in clonal response to

DBH, but these were not statistically significant. DBH of the commercial seedling-based plantation had a lower mean than the clonal value at an equivalent stocking of 1,500 sph.

At age 12.1 there was no evidence of mortality due to internal competition even at stocking of 3,000 sph. The most likely reason for this is the very high productivity of this site.

3.2.- DBH and volume variation across clones and stocking: figure 4 shows the variation in individual-tree DBH and volume by tree as box plots.

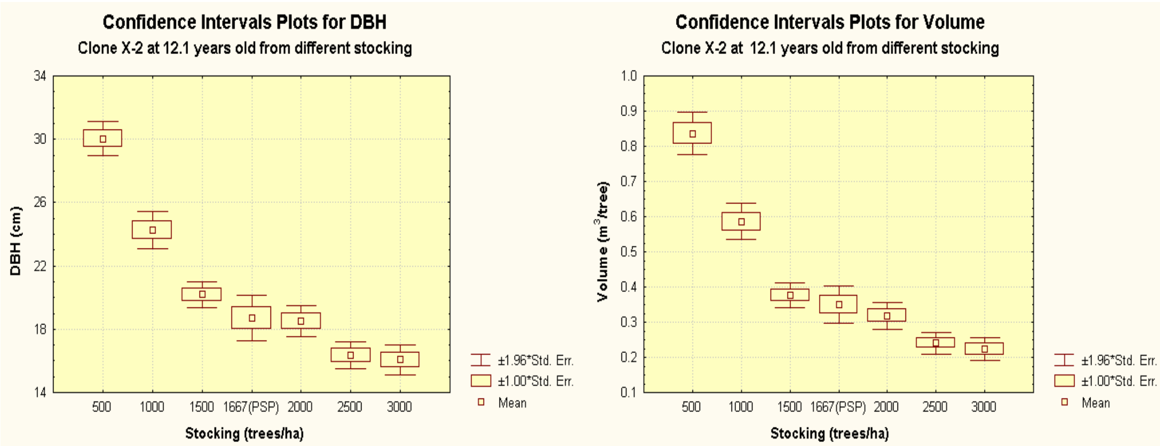


FIGURE 4: Confidence interval plots for DBH and tree-volume for clone X-2 at different stocking levels. Each box shows the mean, ± 1.0 and ± 1.96 * standard errors

A is shown in Table 2 and Figures 5-6, seedlings from the commercial stand had coefficients of variation (standard deviation as a percentage of the mean) for DBH about 60% greater than that for comparable stockings of the clones. Also, there was a trend of reducing variability in DBH with increasing stocking.

TABLE 2:
Estimators for parameters of Gamma distribution for DBH
All Clones at 1500 trees/ha

		DBH [cm]				
				Clone		
		X-2	X-6	X-7	X-8	1667 [PSP]
Shape Parameter	α	15.13474	15.91150	19.07260	11.56346	5.36623
Scale Parameter	β	1.33347	1.28074	1.05061	1.71968	3.51404
Mean	$(\alpha * \beta)$	20.2	20.4	20.0	19.9	18.9
St. Dev.	$\sqrt{(\alpha\beta^2)}$	5.2	5.1	4.6	5.8	8.1
Average STDV for clones					5.2	
Ratio clones vs. Seedlings [PSP]					64%	

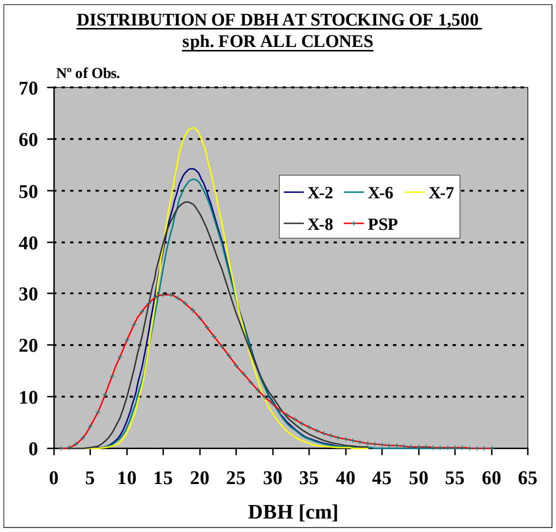


FIGURE 5: Gamma distribution for DBH. All clones at 1,500 sph

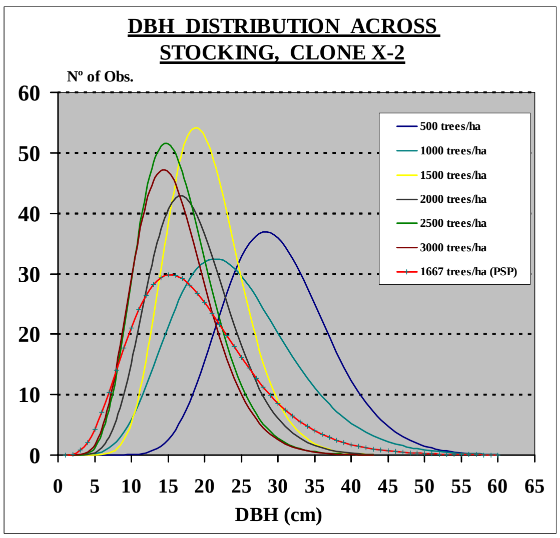


FIGURE 6: Gamma distribution for DBH at all spacing for clone X-2.

The data from PSPs showed both a lower DBH mean [19.9 cm vs. a mean of 20.1 cm for clones], and a wider range. At this stocking, all clones performed similarly in both mean DBH and DBH distribution. Across stockings for clone X-2, there was a consistent trend in reducing both the mean DBH and the amplitude when increasing the stocking.

Commercial seedlings plantations as represented by the PSPs showed a wider DBH distribution than clones at same stocking of 1,500 sph., and their mean DBH was equivalent to that at 2,000 sph. for clone X-2.

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From an operational perspective this issue would be relevant in terms of reducing harvesting costs by decreasing tree size variability through using clones instead of seedlings.

3.3.- Growth modeling: Given the lack of significant differences between clones for most of the variables under analysis, the best clone on TH and DH, named X-2, was considered for growth and yield modeling between ages five to sixteen years across all stocking treatments.

Figure 7 shows the modeling output for both variables, standing volume (SV) and medium annual increment [MAI]. PSP data from the neighboring commercial plantation was also included as reference.

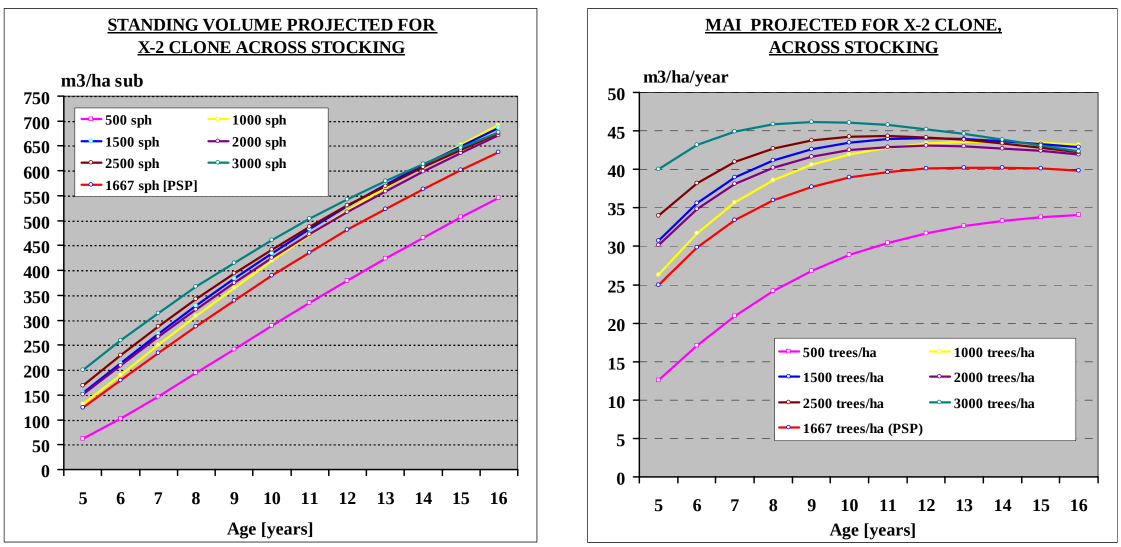

FIGURE 7: Standing Volume and MAI for clone X-2 across stocking

As shown in Figure 7, there is a strong relationship between stocking and standing volume. No significant differences were observed among stockings of 1,000 sph and above for clones at age 12.1 [Duncan multiple range test]. Nevertheless, as expected, the trend in full stocking stands is to converge in the long term and this process tends to be earlier and / or faster when high stocking and high productivity sites occur simultaneously, compared with poorer sites and lower initial stand density (you'd need a reference for this statement, as you only prevent data from one high-productivity site)..

In this case, a stocking of 500 sph. MAI peaked at over 16 years; while at 1,000 sph stocking peaked at 13 years [43.6 m^3 $ha^{-1}y^{-1}$]; 1,500 sph. at 12 y.o. [44.1 m^3 $ha^{-1}y^{-1}$.] and for 3,000 sph. MAI peaked at 9 years, at 46.2 m^3 $ha^{-1}y^{-1}$. Commercial stands with seedlings showed MAI culmination at 13 years with 40.3 m^3 $ha^{-1}y^{-1}$. At age 9, the MAI of clone X-2 over seedlings was around 13.0% higher.

Thus, the issue of defining the initial stocking for maximizing the standing volume will depend on the rotation age and the final desired products. For clones, from a strictly biological perspective, maximum MAI of merchantable pulpwood volume resulted with initial stocking of 3,000 sph. for harvesting ages earlier than 13 y.o. For longer rotation ages, this maximum MAI drops to 1,000 to 1,500 initial trees.

These results for high stockings are quite unusual, because the general knowledge on this indicates that with clones the trend is to get earlier peaks of MAI with lower initial stockings when compared with seedlings, and this relationship is more linear in high productivity sites like the one used this study. Given this fact, the most common trend in countries with intensive silviculture for pulpwood like Brasil, South Africa, Spain, Portugal and Chile has been to reduce the initial stocking when clones have replaced seedlings in commercial plantations [Schönau and Coetzee, 1988; Coetzee, 1991]. Probable reasons for this decision are the extra cost of clonal plants which increases establishment costs, increments on local labor costs, target wood properties are anticipated at earlier ages, improved rates of final survival, changes in structural harvesting costs, and/or changes in final products or prices.

Other usual reason for reducing planting stocking in pulpwood plantations are the harvesting costs. It is very common that, in very steep slopes where the single option for harvesting is by cable logging, the initial stocking trends to be lower than on flat sites, to maximize individual tree volume which is the most important factor in cable logging cost. In the case of flat land, the introduction during the last 25 years of head processors in full mechanized harvesting teams based on harvesters and forwarder machines in pulpwood plantations has been another step ahead in reducing the initial stocking. The harvesting heads which are based on stem-by-stem processing system [including felling, de-branching, de-barking and bucking], are also very responsive to tree size. Producing bigger trees by reducing initial spacing will result in lower harvesting cost per unit of volume.

Nevertheless, it must be noted that for pulpwood plantation the final objective is not producing logs, as in a multi-product plantation. The main target is maximizing the fiber per /ha. Thus, the wood chips rather than logs are the ultimate main raw material before the digester in the pulp mill,.

Recent developments have been made in pulpwood harvesting with road-side mobile chipping machines, which basically are multi-stem or full tree processing systems where the final product is woodchips. These systems are less sensible to tree-size and are more cost-efficient with small trees from high stocking plantations, when compared with traditional harvesting systems. As an additional advantage, the small-end diameter can be reduced and all the by-products from this process are ready to be recovered as bio-fuel [bark, branches and leaves]. This is a very effective way of capturing the total site potential productivity, realizing the economic potential of maximizing the total fiber production from high stocking plantations, and reducing the rotation ages.

<u>3.4.- Economic modeling:</u> Land Expected Value [LEV] was calculated using a discount rate of 10%. For many researchers on Forestry Economics, LEV represents the best and right way to evaluate long term forestry business [Chang, 1984, 1988; Gaffney, 1957, Leuschner, 1990].
The current establishment costs structure considered in this analysis total around US$ 710 ha^{-1} during the first three years, plus an annuity of US$ 46 /ha/yr. for administration, insurance and protection costs. The cost structure includes the nursery production cost for clonal plants [US$ 148.1 per thousand plants) versus US$ 64.8 for seedlings.. The effect of variation on initial planting density higher or lower than the normal stocking at commercial scale [labor cost, fertilization and others was also costed. Similar criteria were applied for harvesting cost [including road costs], where the values ranged from US$ 8.5 m^{-3} to US$ 10.0 m^{-3} under bark at the road side depending on plantation yield [standing volume]. Transport cost was around US$ 6.7 m^{-3} delivered mill yard. Price mill gate was US$ 39.2 m^{-3} under bark

The results for clone X-2 are summarized in Figure 7, across different initial stockings. As the figure shows, the maximum value [LEV peaks] was found for initial spacing between 1,000 to 1,500 s.p.h. with an optimum rotation age around 9 years. Thus, the forestry investor's maximum willingness to pay for a bare land will be around US$ 3,860 /ha if planting clones, meanwhile for seedlings LEV is close to US$ 3,300 /ha, 14% lower than a clonal plantation [- US$ 560 /ha], with a rotation age of 10 years.

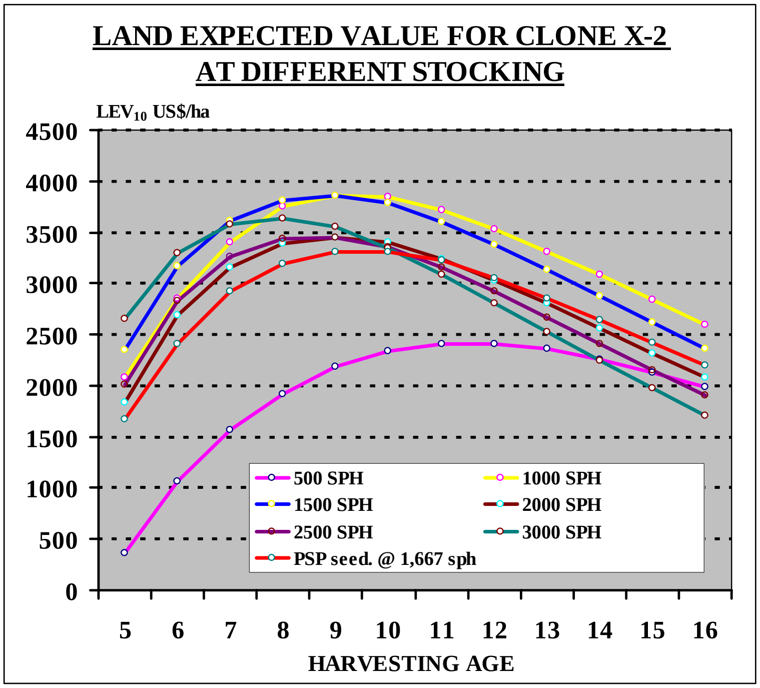

FIGURE 7: Land Expected Value [LEV] by stocking for clone X-2.

When the investor pays land price equal to maximum LEV, the earning will be equivalent to the value of the discount rate, in this case 10%. If the land price is lower, the return will be higher than the discount rate and vice versa. According to Chang, 1984, increment on prices, yield or discount rates tend to move the peak LEV to the left hand side, that is reducing the harvesting age. Meanwhile, increments on establishment cost, reductions on yield or prices tend to produce longer rotation ages. As indicated, the conclusion from the optimum economic criteria is different than the biological one based on the pure maximization of MAI [FIGURE 7]. Here, the cost of the money over the time and the establishment cost differences of increasing or reducing the initial stocking are the relevant factors for both approaches.

If for any reason [for example wood supply constraints] the harvesting age should be reduced to earlier ages than the optimum, then the economic criteria tends to be more similar to the biological one [3,000 sph]. In the opposite case, the conclusion remains the same, with 1,000-1,500 sph being optimum

The slopes of the right and left side of the peak value [optimum] are different: steeper towards early rotations ages and with a probably different decision on initial stocking. Then, any movement to this side must be taken more carefully than to the right side, where any decision tends to be more stable.

Given the above figure, another question arises: how much extra cost would a forestry investor be willing to pay for clonal plants compared with the option of seedlings?. One way for answering this question is by simulation break-even values on the clonal plant cost [or market price] to get LEV clonal = LEV seedlings. In other words, all the extra LEV will be allocated for paying for extra cost clonal plants.

The results are shown in Figure 8.

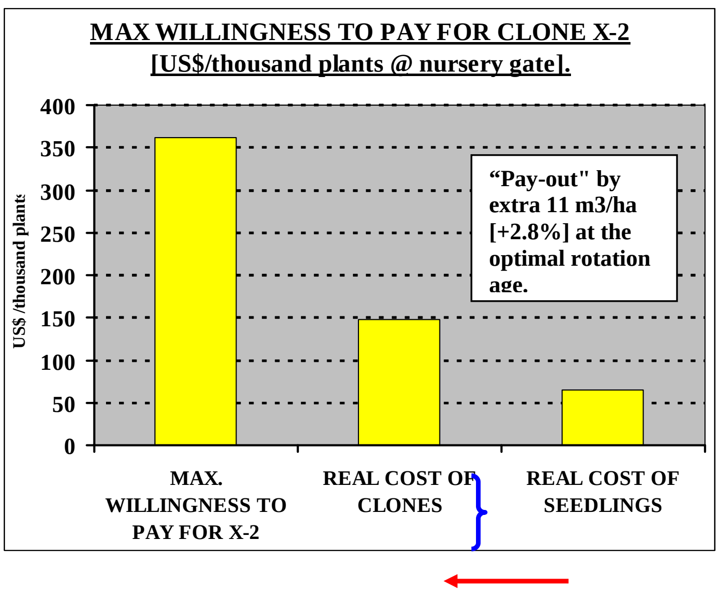

FIGURE 8: maximum willingness to pay for clonal plants.

The real cost per thousand clonal plants is 2.3 times the normal cost of seedlings, meanwhile the maximum willingness to pay given the extra yield and cost structure is 5.6 times more than seedlings. Under this scenario, clonal plant cost could double and still LEV would be higher than seedlings. For paying out the real cost of clonal plants it is necessary to get an extra final volume as low as 11 m^3 ha^{-1}, which represents an increase in total standing volume of 2.8 % over standard seedlings yield. Under these circumstances, the cost of clonal plants become irrelevant in the decision of planting or not planting clones. These results are similar to those found in a previous evaluation of this same trial at age 8.5 [Rodíguez, 2003].

From a strategic point of view, this result is important. Given the current trend of forestry business, becoming more and more concentrated with fewer big players, more focused on an expanding global commodities market and with pulp and paper prices declining in real terms, the issues of: [1]increasing yields of existing land; [2] being able to acquire new more expensive land and finally; [3] expanding industrial capacity are key factors for short and long term competitiveness and for increasing the return over total capital employed [ROACE]. In this sense, investing in tree breeding technology and realizing gains in the field are one of the most profitable strategies.

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