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Diameter-Density Relationships Provide Tentative Spacing Guidelines for *Eucalyptus saligna* in Hawaii

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Trials have been established in Hawaii to develop spacing guidelines for *Eucalyptus saligna* plantations. Substantial competition-related mortality occurred in densely planted plots of three spacing trials. Data on stand diameter and surviving number of trees on these plots were plotted in logarithmic form to estimate a "self-thinning" or maximum diameter-stand density line. An "operating" maximum line was defined—one representing 70 percent of the total number of trees that could reach any given mean diameter if the stand were allowed to reach the "self-thinning" level. This information provides a guide to the number of *E. saligna* trees to plant per hectare for selected target diameters at harvest.

Retrieval Terms: *Eucalyptus saligna*, diameter-density relationships

Intensive culture of tree plantations to produce biomass for energy generation is being assessed in Hawaii. A number of species and cultural treatments are being tested, but much attention has centered on *Eucalyptus saligna* (Sm.) because of its excellent survival and growth on a wide range of sites.[1] Although many plantations of *E. saligna* and other eucalypt species have been established in Hawaii and elsewhere,[2] information on spacings for production of fiber and fuel in short-rotation plantations is scant. Such plantations are characterized by dense spacing and by rotations or cutting cycles of 10 years or less.

One spacing trial was established with *E. saligna* on the island of Maui, Hawaii to test a range of spacings for sawtimber production. Information was collected for 15 years,[3-5] after which the study had to be ended because of severe wind damage. Since then, several new trials have been established at much closer spacings on the island of Hawaii. These trials are too young to answer many of the questions associated with spacing, such as rotation length and yield. A critical factor in spacing decisions, however, is the desired tree size at harvest—generally expressed as average stand diameter at either rotation age or first commercial thinning.

Considerable competition-related mortality (self-thinning) has occurred in the densest plots of two of the newer spacing trials, and self-thinning had also occurred in the densest treatment of the Maui trial before its final measurement. Data on tree survival and average stand diameter from selected plots in these three trials were used to study the relationship of diameter to stand density.

This note proposes a guide for planting density or initial spacing of *Eucalyptus saligna* in Hawaii based on the relationship of stand density to maximum tree diameter.

METHODS

Data on tree size and density were obtained from seven plots in the three *E. saligna* spacing trials—one on Maui, and the two others on Hawaii at Akaka Falls and Ka'u. Criteria for plot selection were: (1) initial stocking levels exceeded 1000 trees per hectare, and (2) mortality was related primarily to competition and exceeded 20 percent.

The Maui trial was at 150-m elevation on a well-drained silty clay soil and had about 3800 mm of rain annually.[3] Data collected at stand ages 5, 10, and 15 years from three plots in the 2.4-m by 2.4-m spacing treatment were used in the present study. The Akaka Falls study was established at 480-m elevation on the northeast coast of the Island of Hawaii, where rainfall averages about 4000 mm. The soil is a silty clay loam and had been in cane production for several decades. Two plots were selected from the densest spacing (1 m by 2 m) of this trial; measurements were available for stand ages 2, 4, 5, and 6 years. The Ka'u study was established at 650-m elevation on the southeast coast of the Island of Hawaii, where rainfall is about 1850 mm. The soil there is an extremely stony, silty clay loam. Two plots were selected from the 1-m by 2-m spacing treatment of this study. Measurements had been made at stand ages 1, 2, 3, and 4 years.

Periodic measurements of quadratic mean diameter were plotted against corresponding stand density (number of trees per hectare) on logarithmic scale to verify that self-thinning was in progress, and to approximate the level of a self-thinning line for *E. saligna*. A diameter-density relationship was developed by assuming a slope of -1.6 as used by Reineke[6] and establishing the elevation (intercept) visually based upon the final or latest measurements of each plot.

The proportion of suppressed trees in plots approaching or attaining the self-thinning asymptote was determined and used to define an "operating maximum" line. This line was then used to develop recommendations on planting density (or initial spacing) for various mean stand diameters desired at harvest.

We compared the results with published data from undisturbed species trials, spacing tests, and growth and yield studies involving *E. saligna* and the closely related *E. grandis* in other geographic areas.

RESULTS AND DISCUSSION

Diameter-Density Relationships in Hawaii

A decline in number of trees per hectare caused by self-thinning occurred in all selected plots as mean diameter of the stand increased *(fig. 1)*. This decrease averaged 26 percent, ranging from 20 to 36 percent. For the dense plots at the Akaka Falls and Ka'u studies, these losses ranged from 1000 to 1800 trees per hectare.

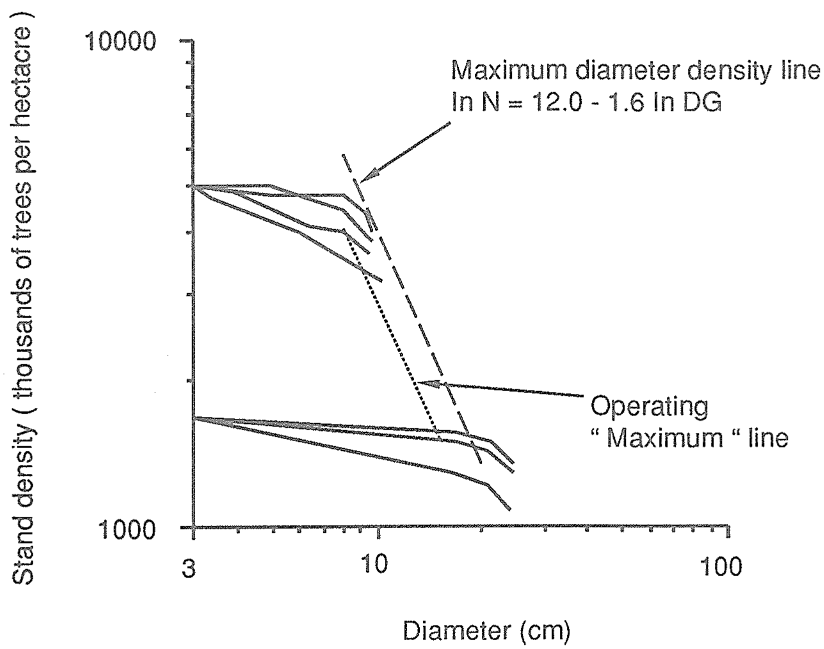

Figure 1—Relationships between stand density (N) and mean stand diameter (Dg) for *Eucalyptus saligna* in Hawaii.

Similar relationships between size and number of surviving plants have been demonstrated for many tree and herbaceous species.[7] The Reineke line as used in our study is very closely related though not identical to the "self-thinning rule" or the "-3/2 power law" based on mean volume.[8] Within rather wide limits, these relationships are independent of stand age and site quality or fertility level. Thus, we considered it reasonable to use the Reineke relationship in combination with data from the three different spacing trials in Hawaii to estimate a maximum mean diameter-stand density line.

The equation form for the relationship is:

$$\ln N = 12.0 - 1.6 \ln Dg$$

in which N is number of trees per hectare, and Dg is quadratic mean diameter (cm).

Comparison with Other Trials

Comparative information for *E. saligna* and *E. grandis* (Hill) Maiden in other regions is scant. Although several spacing trials and growth and yield studies exist for these species, many data were unsuitable for comparison with our results because mortality or residual stand density was affected by factors other than competition—for example, thinning,[2] freezes,[9] and drought.[10] In some instances, data on numbers of trees per hectare at various ages and sizes were not provided or the extent and cause of mortality were not mentioned, or both.[2,11,12]

Results from two plantations in New South Wales, Australia—a species trial near Dungog and an unthinned *E. grandis* plantation at Coffs Harbour—provide a few comparative points.[13] The species trial was planted at 2.4 m by 2.4 m (1740 trees per hectare). At 15 years, mortality was 27 percent for *E. grandis* and 21 percent for *E. saligna*, and diameters were 19.7 cm for *E. grandis* and 18.0 cm for *E. saligna*. Density in the unthinned plantation decreased from 1423 trees per hectare at age 5 to 1097 trees per hectare at age 16; mean diameter increased during the same period from 12.2 to 20.2 cm. A correlated curve trend spacing trial for *E. grandis* in Zululand, Republic of South Africa provided two additional points for comparison.[14] Harmonized estimates of diameter for two treatments in this trial were plotted against actual numbers of trees per hectare. Stand density in one treatment had dropped from 2965 trees per hectare at year 1.3 to 1639 trees per hectare at year 22 when estimated diameter was 20 cm. Tree numbers in the other treatment had decreased from 1482 at year 1.8 to 1203 at year 22 when diameter attained 24 cm. The final diameter-density values for those five studies plotted reasonably close to our estimate of the maximum diameter-density line for *E. saligna*; the Australian values are slightly below and the South African values are slightly above the line.

Guide to Planting

The maximum number of trees that can be grown to a given mean stand diameter can be estimated by the "self-thinning" asymptote, but considerable mortality will occur before the stand attains this stage of development *(fig. 1)*. Thus, stocking guides commonly define a line that indicates the lower limit of the self-thinning zone[15] or an operating "maximum."[16] For many species growing in "normal" or fully stocked natural stands, the self-thinning zone consists of 35 to 40 percent of the total number of trees, most (if not all) of which are suppressed.[15,16] The presence of such trees adds little to total stand volume or biomass. Their establishment in plantations, however, would increase costs in proportion to their number for planting and some other cultural practices (e.g., application of fertilizer, which in our Hawaiian *Eucalyptus* plantations is made to individual trees during the first 2 years).

We have, therefore, defined an operating "maximum" line, which estimates the number of trees to establish for given target diameters *(fig. 1)*. This line represents 70 percent of the total number of trees that could attain a given mean diameter if the stand were allowed to attain the self-thinning asymptote. Choice of this level was based on two considerations: (1) it occurs within the zone where some trees are dying from competition-related factors, and (2) examination of basic data from the latest measurements at the Akaka Falls and Ka'u trials showed that 30 percent of the trees were irreversibly suppressed. Using this operating maximum line, we estimated the number of *E. saligna* trees to plant per hectare (and the effective square spacing) for selected target diameters at harvest:

Target stand diameter	Trees per hectare	Growing space per tree	Approximate square spacing
cm	*no.*	*m²*	*m*
6	6480	1.5	1.2
8	4090	2.4	1.6
10	2860	3.5	1.9
12	2140	4.7	2.2
15	1500	6.7	2.6
20	950	10.5	3.2
25	660	15.2	3.9
30	490	20.4	4.5

The relationships reported herein represent first approximations—and should be reexamined and refined as more data become available. Moreover, the planting recommendations assume that no thinning will be done and that mortality due to causes other than competition is minimal. If such assumptions are not appropriate, planting density should be increased accordingly.

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