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Insights from full-rotation Nelder spacing trials with *Eucalyptus* in São Paulo, Brazil

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The choice of spacing among trees for operational plantations is typically based on one or more experimental plantations that test for the response of tree and stand growth to a range of tree-to-tree distances. The most common design for spacing experiments entails rectangular plots that test different distances between rows, and between trees within rows, and with replication of plots covering one to several hectares within a single stand. Other designs may offer more information with simpler layouts, and we examined the insights that could be obtained from a Nelder (fan-shape) design, where spacing among trees varies with the radial distance from a central point. The response of *Eucalyptus dunnii* seed-origin trees to spacing was essentially similar between a classic plot design replicated in four blocks (tree spacing from 4.5 to 9.2 m^2 tree^{-1}, covering 1.4 ha of land), and a Nelder design (tree spacing from 2.1 to 44.0 m^2 tree^{-1}, covering 0.6 ha of land). The Nelder design showed slightly higher volume increment through 10 years of stand development than the block design (for the range of overlap in spacing), but the treatment effect of spacing was essentially identical between the designs at the level of both trees and stands. A second Nelder experiment used clonal-origin trees from six clones, testing for differences in responses to spacing among clones. In all three spacing experiments and for all clones, individual-tree growth was greatest at the widest spacing and stand-level growth was highest at the tightest spacing. These trends were much clearer across the wider range of spacing tested in the Nelder plots (228 to 4 760 trees ha^{-1}) than in the narrower range of spacing tested in the block design (1 111 to 2 222 trees ha^{-1}). Current annual increment reached a higher, earlier peak at narrow spacing. At 8.5 years, the light use efficiency (stem volume growth per unit of light intercepted) was about twice as great for trees at narrow spacing than at wider spacing. Overall, the Nelder designs provided the same information on responses to spacing as the classic block design. The simplicity and small size of Nelder designs provide valuable insights for basic decisions on spacing for operational plantations, particularly when forestry extends into new geographic areas, new genotypes, and new silvicultural techniques.

Keywords: *Eucalyptus* clones, *Eucalyptus dunnii*, forest growth and yield, leaf area, light use efficiency, sawlog production

Introduction

One of the most fundamental questions in plantation forestry is 'what is the best spacing between trees?' The answer depends on several factors, including the costs of establishing the plantation, the three-dimensional structure of canopies, competition between trees for resources, the costs of harvesting, and the value of wood products. High densities provide greatest growth per hectare, likely as a result of rapid development of the forest canopy and high rates of capture of resources (light, water and nutrients). Lower densities provide for larger individual stem sizes, which may provide higher value per cubic metre of wood. The interactions of these environmental and economic factors is so important that no single choice of tree spacing will be universally optimal. Site-specific choices for tree spacing in *Eucalyptus* plantations often range from 800 to 2500 trees ha^{-1}, with the decisions based on local spacing trials, coupled with analyses from growth and yield models (Gerrand and Neilsen 2000).

Thousands of spacing trials have been planted around the world, yet the need for new trials continues as foresters innovate with new genotypes and species in new areas, with new silvicultural systems optimised for various products. The most common design for spacing trials often tests three or four levels in small rectangular plots, with three or four replicate plots placed within an area of a few hectares (Walters 1973, Gonçalves et al. 2004, Pretzsch 2009). This general design has been very informative, but it is limited in two important ways. The investigation of three or four discrete spacings limits the range of inference, and may make it difficult to discern between linear effects and modestly curvilinear effects. More critically, nesting all replicates within a single location provides a population of inference of just a single stand (Binkley 2008). The results of spacing trials are applied across very large areas with substantial variation in site conditions, so nesting replicates within a single site requires bold assumptions about the consistency across geographic gradients.

These two limitations can be accommodated by the use of experimental designs that test a wide range of spacings in designs that are simple enough to be replicated easily across the geographic area of interest. Nelder (fan-shape) designs are one such approach (Nelder 1962, Namkoong 1966, Panetsos 1980, Imada 1997), where planting in radial designs provide several-fold ranges in spacing in relatively small areas (Figure 1). Nelder designs also have some potential limitations (Freeman 1964, Huxley 1985). For example, trees that represent narrow, high-density spacing are located in a relatively small area near the centre. If the site has any notable variation in soil properties, this small centre area might have a high tendency to deviate from the typical site conditions. A gradient in slope or soil properties across the Nelder plot might provide another source of error across spacing levels. Nelder designs can be problematic if mortality is substantial, given the relatively low number of trees that represent each spacing level. Spatial statistical techniques may be needed to estimate the values for missing trees (e.g. Oda-Souza et al. 2008). These potential limitations may be critical in some locations with variable topography and soils. Overall, Nelder designs provide clear indications of the main effects of spacing on more uniform sites, and the small land area required for each experimental installation facilitates more replication across landscapes.

We report on the insights from two Nelder experiments, addressing three questions:

(1) Does the Nelder design lead to the same insights on spacing patterns as classic plot-based designs?
(2) What insights can be obtained from unusually wide spacings?
(3) What insights can a Nelder design provide into the effects of spacing on production ecology?

We hope these examples will spur broad-scale application of similar designs.

Methods

The research site was on the Ibiti farm of Conpacel Company (formerly Ripasa Pulp and Paper) located in Itararé, São Paulo state (24°11′ S, 49°08′ W, elevation 980 m). During this study, annual average temperature was 19.9 °C, and precipitation varied from 1 250 mm y^{-1} to 1 600 mm y^{-1}. The soil is a deeply weathered oxisol (Haplic Acrorthox) developed in siltstones and mudstones of the Itararé geologic formation. Clay content increases from 48% in the topsoil to 58% in the B horizon, with bulk density declining from 1.3 kg l^{-1} in the topsoil to 1.2 kg l^{-1} in the lower profile. The upper metre of soil contained 2–3% organic matter, with a soil pH_{KCl} of 3.5–4.0 and low base saturation (<10%). This subtropical site with high clay content probably experiences no water limitation on tree growth, so the patterns that developed in these experiments should not be extrapolated to drier sites.

Question (1) was addressed by comparing growth of *Eucalyptus dunnii* seedlings in a fan-shape Nelder design, and in a replicated block design for 10 years. Seeds were obtained from an open-pollinated source in Australia (Lot #480). Seedlings were grown in 50 ml tubes in a substrate of 90% composted eucalypt bark and 10% ash from a biomass boiler. Seedlings for planting were chosen after 90 d, selected for vigorous condition and heights of 30–35 cm. Site preparation included harrowing, and initial fertilisation provided 25 kg N, 24 kg P, and 21 kg K per hectare. Lime was also added at 39 months at a rate of 4 Mg ha^{-1}. Weeds were controlled with herbicide applications.

The replicated block design was planted in March 1988 with four levels of spacing (3.0 m × 1.5 m, 3.0 m × 2.0 m, 3.0 m × 2.5 m, and 3.0 m × 3.0 m, providing 4.5–9.2 m^2 $tree^{-1}$ and 1 111–2 222 trees ha^{-1}). Each spacing was tested in each

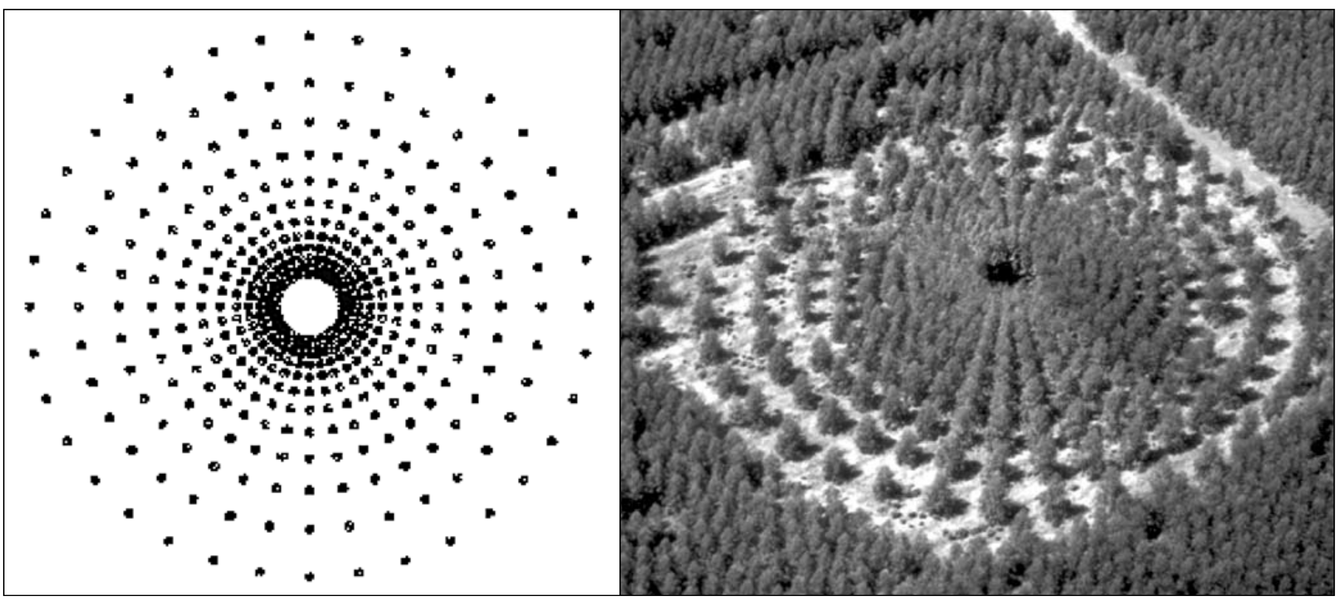

Figure 1: Diagrammatic representation and photograph (at 10 months) of the Nelder design with 36 rays and 12 arcs. The two interior circles (termed arcs) of trees, as well as the outermost circle, were used as buffers and not included in the analysis. The diameter of the circle is 87 m, with an area of 0.6 ha

block in 27 m × 27 m plots; the interior 25 trees (five rows × five columns) were used for measurements. For the Nelder design (Figure 1), 36 rays were planted in 12 circles (or arcs, in common Nelder terminology) with trees at distances (from the centre) of 5.3 m, 6.4 m, 7.8 m, 9.4 m, 11.4 m, 13.8 m, 16.7 m, 20.3 m, 24.6 m, 29.7 m, 36 m, and 43.6 m. The first two trees (arcs) near the centre of the plot, and the final arc of trees were used as buffers providing a range of spacings from 2.1 m^2 $tree^{-1}$ to 44 m^2 $tree^{-1}$ (228–4 760 trees ha^{-1}). The sector area available to each tree was almost rectangular, with a ratio of width to length of 0.91, mimicking typical rectangular layouts in commercial operations.

Tree diameters (breast height) and heights were measured periodically for 10 years and total stem volumes were determined from destructively sampled trees at five ages (25, 42, 61, 70, and 116 months; Table 1) from buffer areas around the experimental plots. Case-specific regressions typically have greater precision in *Eucalyptus* plantations in Brazil than generic equations (Stape et al. 2010). Values for the stand level were simple sums of the estimated stem volume of each tree in the plot.

Questions (2) and (3) were also examined in these *E. dunnii* plots, as well as in an adjacent Nelder experiment using clonal trees. The second experiment used two clones of *E. saligna* (#04-045-03 and #04-033-01) and four clones of *E. grandis* (#03-254-33, #03-059-02, #03-059-03 and #3-058-03). Each clone was planted in a wedge with six rays using the same design as in the *E. dunnii* Nelder experiment. All treatments and measurements were the same as in the other Nelder, with additional measurements when the experiment was harvested at the end of the rotation (8.5 years). A regression equation was developed from harvested trees at four ages to estimate volumes from diameters and heights (Table 1). Survival was over 98%; for each planting location where a tree died, the adjacent trees were omitted from the analysis.

Tree leaf area was determined at the end of the clonal experiment by destructively sampling the canopies of half of the trees in each spacing for four of the clones (the worst, the best, an intermediate, and a clone used in many experiments by the company). All leaves were stripped from the trees and weighed in the field for each individual tree. Well-mixed subsamples were oven-dried and measured for specific leaf area with a scanner system. The relationships between tree diameter, height and leaf area varied among the clones, so separate equations were used for each clone (Table 1).

Light interception increases asymptotically with increasing leaf area, and we estimated light interception using Beer's Law:

$$\text{Intercepted light} = (1 - e^{-k(\text{LAI})}) \times \text{incoming light}$$

where k is the light extinction coefficient, and LAI is the leaf area index. We did not measure the light extinction coefficient in this experiment. Given that the three-dimensional structure of the canopies differed among spacings, the coefficient may have varied with spacing. Therefore, we calculated light interception in two ways: (1) assuming a constant coefficient of 0.36 (Stape et al. 2004), and (2) with an extinction coefficient that ranged linearly from 0.5 at 2.1 m^2 $tree^{-1}$ to 0.3 at 44.0 m^2 $tree^{-1}$ (Landsberg and Waring 1997).

Analysis of the effects of density and age at the level of stems and stands were performed with SYSTAT 11 (Systat Software, Chicago) and SigmaPlot 8.0 (Aspire Software International, Ashburn, Virginia). A p value of 0.05 was chosen to minimise the risk of Type I errors.

Results

The range of spacings from 4.5 to 9.2 m^2 $tree^{-1}$ in the classic block design with *Eucalyptus dunnii* seed-origin trees led to a two-fold range in the volume (0.12–0.25 m^3 $tree^{-1}$) of individual trees (Figure 2). The trade-off between larger tree size at wider spacing was offset by fewer trees per hectare, leading to no significant difference in stand-level volume (about 290 m^3 ha^{-1}) or increment. This common pattern across typical ranges of operational plantings has been also been reported on by Skovsgaard and Vanclay (2007).

The wider range of spacing in the Nelder design also provided the expected pattern of increasing individual-tree volume and growth with wider spacing (Figures 3 and 4) for *Eucalyptus dunnii*. The Nelder experiment used less land area, and produced a very clear pattern in stand-level volume and increment (unlike the classic plot design) with the widest spacing yielding only half the stand volume (150 m^3 ha^{-1}) of the narrowest spacing (340 m^3 ha^{-1}). The Nelder results are illustrated with separate lines for each spacing over time in Figure 3; Figure 4 presents the same information with isolines showing volume (or increment) as a function of spacing and age; and the equations for these relationships are presented in Table 2.

Question (1) asked whether the Nelder design would provide the same insights about spacing patterns as classic block designs. The two approaches did show very similar patterns across the same range of spacing (Figure 5), although the Nelder values tended to be about 10–15% higher than the block-based values for the overlapping range of spacings. The trade-off between volumes of individual trees and stands was much more apparent in the

Table 1: Regression equations for total stem volume and leaf area. Volume is m^3 $tree^{-1}$, diameter at breast height (dbh) is in cm, height (h) is in m, and leaf area is m^2 $tree^{-1}$. All equations are significant at $p < 0.0001$

Predicted variable	Equation
Stem volume for *Eucalyptus dunnii*	Stem volume = 0.00004 $dbh^{1.99} h^{0.99}$, $n = 115$, $r^2 = 0.995$
Stem volume for *Eucalyptus* clones	Stem volume = 0.00005 $dbh^{1.89} h^{1.01}$, $n = 356$, $r^2 = 0.996$
Leaf area for Clone 1	Leaf area = 0.04306 $dbh^{3.97} h^{1.64}$, $n = 28$, $r^2 = 0.97$
Leaf area for Clone 2	Leaf area = 1.83547 $dbh^{3.67} h^{2.48}$, $n = 28$, $r^2 = 0.87$
Leaf area for Clone 3	Leaf area = 1.68877 $dbh^{3.59} h^{2.40}$, $n = 29$, $r^2 = 0.79$
Leaf area for Clone 4	Leaf area = 0.01600 $dbh^{3.11} h^{0.57}$, $n = 30$, $r^2 = 0.88$

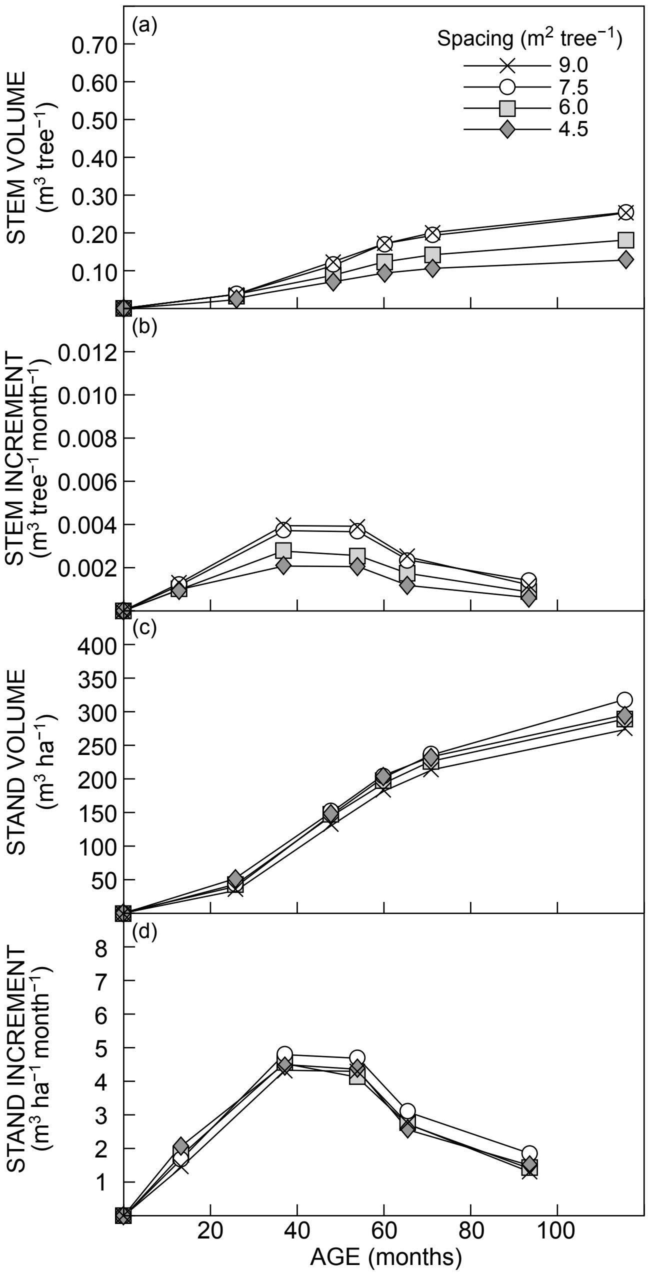

Figure 2: Tree and stand volume and increment for *Eucalyptus dunnii* seed-origin trees in the classic block design. Individual tree volume and increment with increasing spacing per tree, whereas stand volume and increment did not differ significantly with spacing

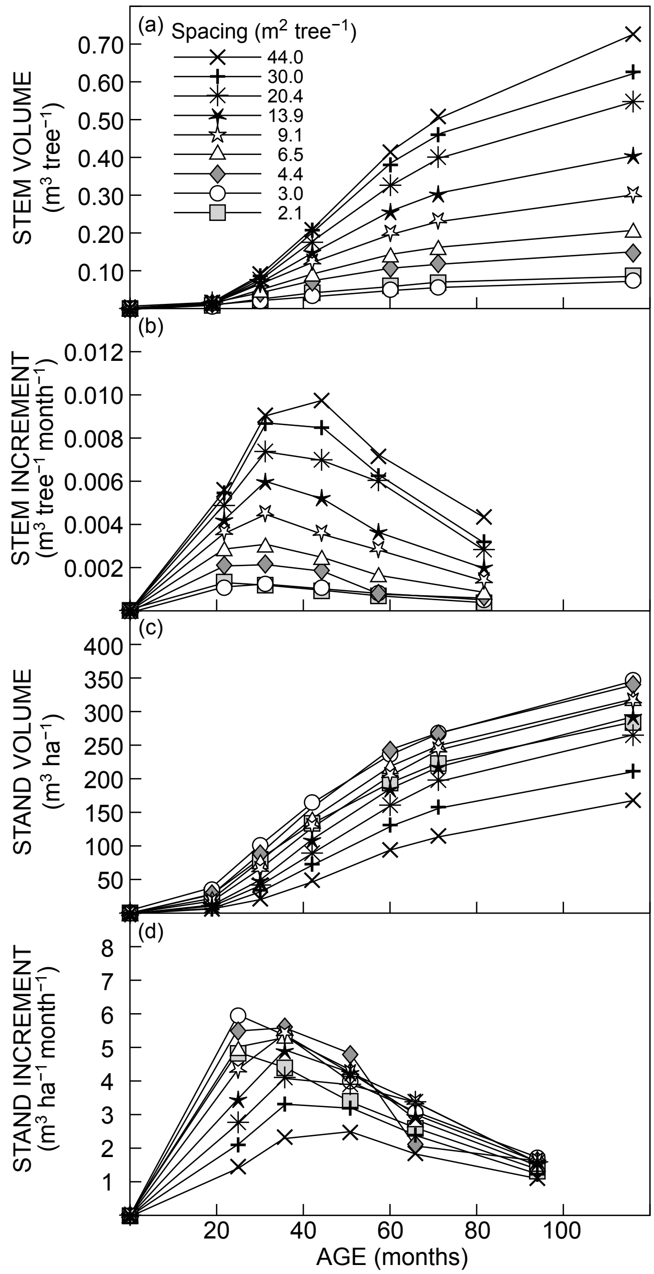

Figure 3: Tree and stand volume and increment for *Eucalyptus dunnii* seed-origin trees in the Nelder design. At the tree level, volume and increment increased with spacing, whereas both decreased with spacing at the stand level (see also Figure 4)

Nelder design. The actual growth rates that would develop across a forested landscape cannot be captured by the growth rate at a single experimental site (cf. Schönau and Coetzee 1989, Louw and Scholes 2002), so the value of a spacing trial lies more in the relative response of growth (or volume) to spacing rather than the precise estimate of growth (or volume). Any operational recommendation for spacing would be the same for the block and Nelder trials.

The second question dealt with insights that could be obtained from wider spacings than are commonly tested in spacing trials. Several points are evident from the figures. Firstly, the trend between spacing and volume and growth at the stand scale was very clear in the Nelders (given the wide range of spacings). The narrow range of spacings in the classic block design was not broad enough to demonstrate this commonly expected pattern. Secondly, Figures 3a, 4a and 6a provide a clear indication of how long it takes to produce a tree of any desired volume, in relation to spacing. A target size of 0.3 m^3 $tree^{-1}$ (a common target for operational silviculture in Brazil; cf. Martins et al.

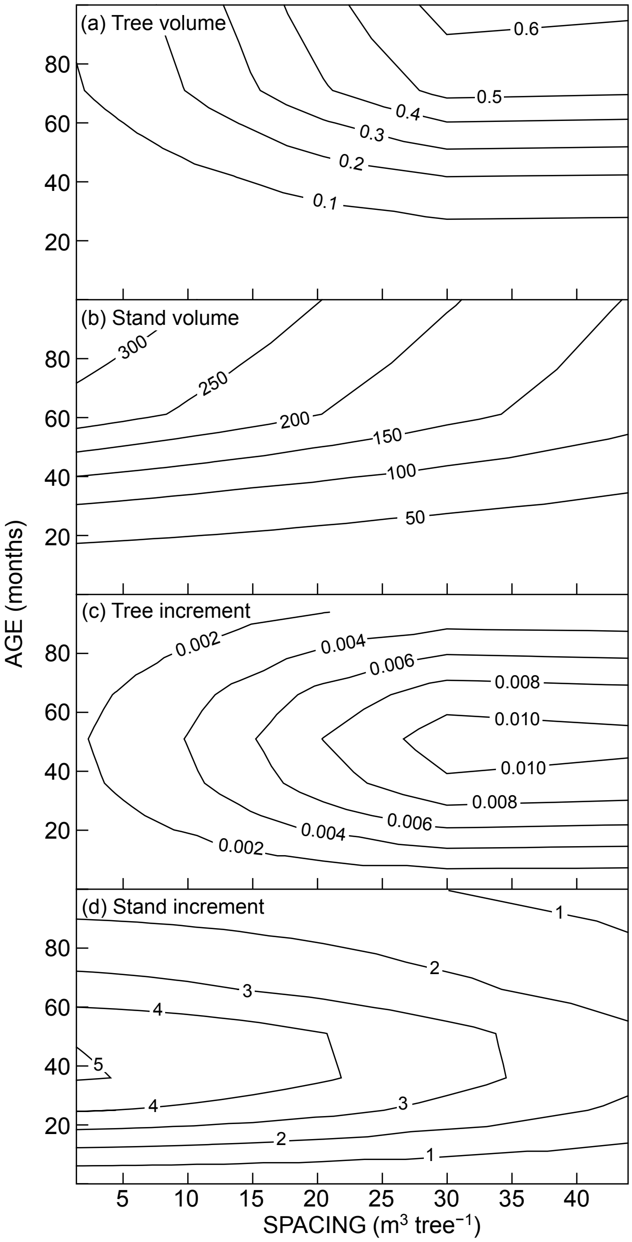

Figure 4: Pattern of tree volume and stand volume (m^3 ha^{-1}) and tree and stand increment (m^3 ha^{-1} $month^{-1}$) from the Nelder design with *Eucalyptus dunnii* seed-origin trees, as a function of spacing and age

2009) would take in the order of 50 months for spacings greater than 30 m^2 $tree^{-1}$ or 100 months at spacings less than 12 m^2 $tree^{-1}$. Thirdly, the tradeoffs between large trees at wide spacings and high stand volumes at narrow spacing are particularly evident in the Nelder results (Figure 5c and d). Finally, the desired products from a plantation may be different in the future, and the wider spacings in the Nelder design provide growth and yield information about plantation management aimed at sawlog production (Malan 2005). The Nelder designs provide a broad suite of potential information (including canopy architecture) that can be critical for informing (and validating) models that might be developed for growth and yield, as well as process-based models of production.

The third question dealt with insights into the production ecology of plantations. The Nelder designs showed that the peak growth rate per tree increased with increasing spacing (Figure 7a). This pattern was evident in the classic block design as well, but the Nelder design revealed the non-linear, asymptotic limit beyond about 30 m^2 $tree^{-1}$. The peak rate of growth in the classic block design did not show a relationship with spacing, whereas the Nelder designs clearly showed that peak stand growth declined linearly with increased spacing (Figure 7b). Intriguingly, the time at which peak growth occurred was delayed with increased spacing. The causes of declines in forest growth as relatively young forests increase in age is a topic of great research interest (Gower et al. 1996, Ryan et al. 2004, 2010, Stape et al. 2010). These patterns of peak growth in relation to spacing do not provide a ready explanation for age-related decline, but they provide a clear challenge that would need to be accommodated by any mechanistic explanation.

The measurement of leaf area at 100 months also provided insights into the production ecology of the *Eucalyptus* clones. Not surprisingly, tree leaf area increased strongly with increasing spacing of trees (Figure 8a). This trend was largely countered at the stand level by the declining tree numbers at the stand level to produce a much more limited range of LAI values, ranging from LAI of about 2.2 at tight spacings to a maximum of about 3.2 at about 25 m^2 $tree^{-1}$, declining with increasing spacing to about 2.6 (Figure 8b).

Our approximations of light interception showed that light interception at the stand level may have differed by about one-third across the range of spacing, whether the light extinction coefficient was held constant or varied (Figure 8). The key feature driving higher stand growth at narrower

Table 2: Equations for volume and increment of stems and stands as a function of spacing and age (plotted in Figure 4). Volume is given as m^3 $tree^{-1}$ or m^3 ha^{-1}, spacing (S) as m^2 $tree^{-1}$, increment as m^3 $tree^{-1}$ $month^{-1}$ or m^3 ha^{-1} $month^{-1}$, and age (A) is given in months. All equations are significant at $p < 0.0001$

Predicted variable	Equation	
Eucalyptus dunnii	Tree volume $= 0.795\,e^{-0.5\left[\left(\frac{S-36.28}{18.42}\right)^2+\left(\frac{A-101.51}{36.73}\right)^2\right]}$	$r^2 = 0.97$
	Stand volume $= 722.520\,e^{-0.5\left[\left(\frac{S-80.36}{71.25}\right)^2+\left(\frac{A-101.66}{40.50}\right)^2\right]}$	$r^2 = 0.97$
	Tree increment $= 0.012\,e^{-0.5\left[\left(\frac{S-35.89}{17.87}\right)^2+\left(\frac{A-49.56}{26.43}\right)^2\right]}$	$r^2 = 0.91$
	Stand increment $= 5.345\,e^{-0.5\left[\left(\frac{S-5.34}{38.27}\right)^2+\left(\frac{A-42.65}{24.57}\right)^2\right]}$	$r^2 = 0.77$

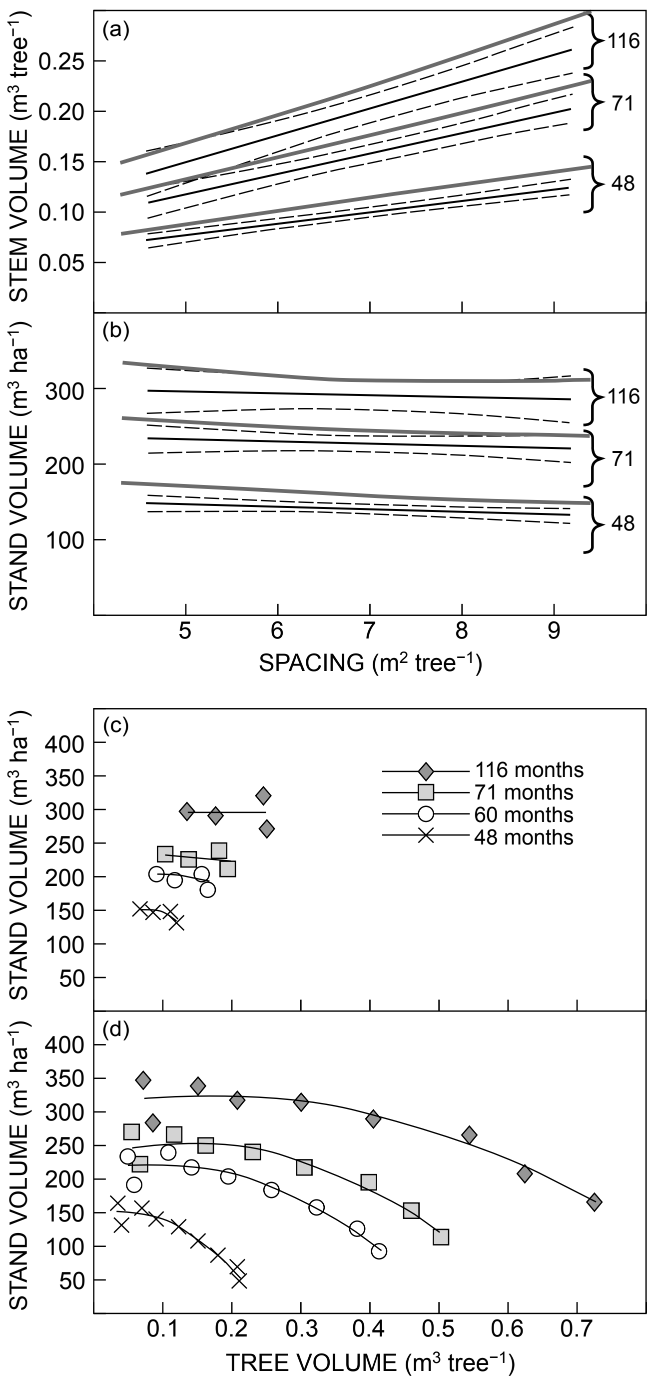

Figure 5: Stem volume (a) and stand volume (b) as a function of spacing (X-axis) and age (months denoted at the right of each graph) for *Eucalyptus dunnii* seed-origin trees in a classic block design. Thin solid lines represent the trend with spacing in the classic block design, and dashed lines indicate the standard error of the estimate. The heavy line for each of the three periods is the best-fit line from the Nelder design for the same range of spacing. Values from the Nelder plot tended to be 10–15% higher than observed in the classic block design, but the patterns were consistent for both designs, providing the same insight about the effect of spacing for operational implementation. The trade-off between volume of individual (mean) trees and stands was much clearer in the Nelder design (d) than in the block design (c)

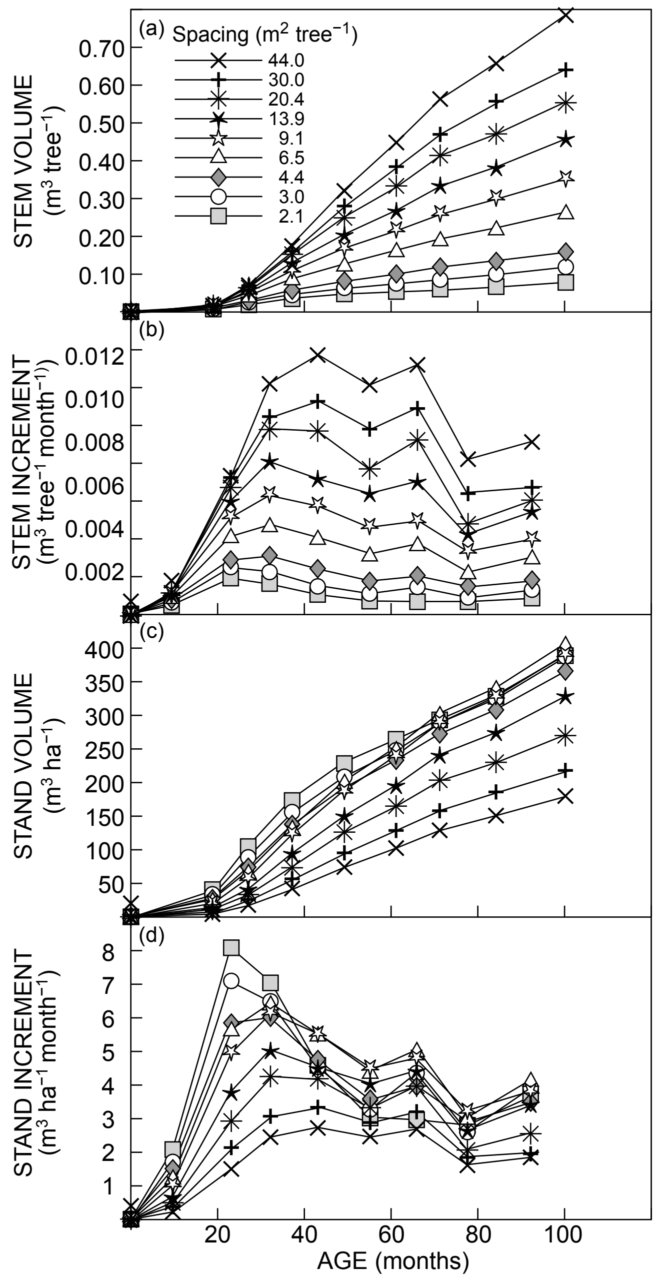

Figure 6: Tree and stand volume (a and c) and increment (b and d) for *Eucalyptus* clonal trees in the Nelder plot. At the tree level, volume and increment increased with spacing, whereas both decreased with spacing at the stand level

spacings was the greater efficiency of using light (Figure 8d). What would account for a two-fold range in light use efficiency with spacing? Three causes may be important. Trees growing at wider spacings undoubtedly invest more photosynthate in branch growth to sustain wider canopies, so basing light use efficiency on total woody production, rather than only stem production, might show smaller differences in efficiency of light use in relation to spacing. In addition, trees at wider spacings might allocate more photosynthate below ground, leaving less for wood growth. Finally, the

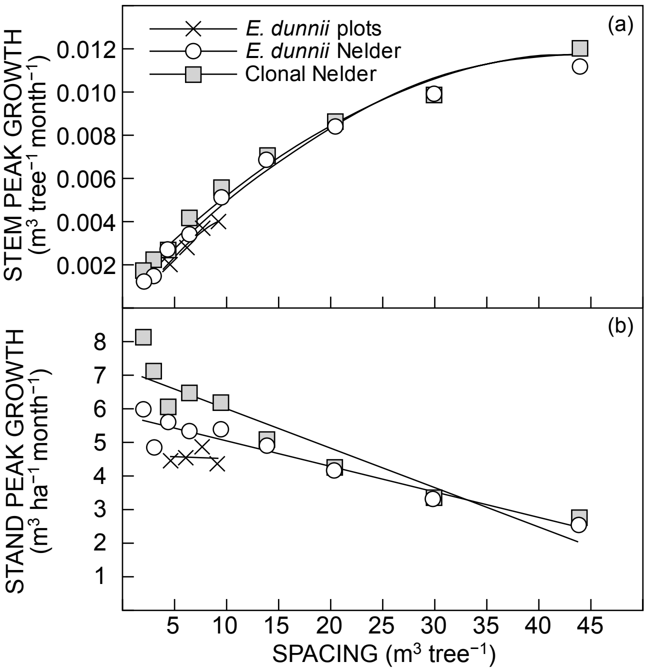

Figure 7: The peak growth rate per tree increased with increasing spacing (a), and was similar for all three experiments. The peak in stand volume growth (b) declined substantially with increased spacing in the Nelder plots (*Eucalyptus dunnii* Nelder r^2 = 0.92, clonal Nelder r^2 = 0.86), but no trend was apparent for the block experiment with the limited range in spacing

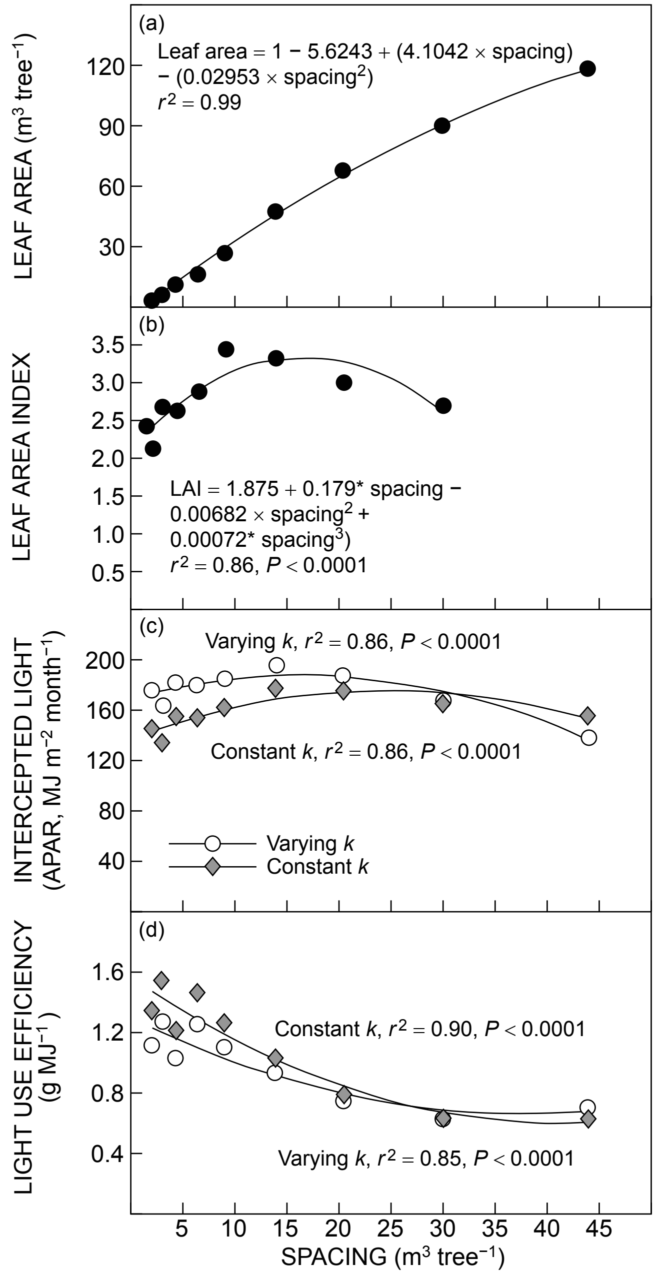

Figure 8: Leaf area per tree at 100 months in the clonal *Eucalyptus* Nelder experiment increased by more than an order of magnitude with increased spacing (a), whereas stand leaf area index (LAI) differed by less than a factor of two (b). Light interception at the stand level differed even less than LAI, but stem growth per unit light intercepted (c) declined by about half with increasing spacing (d). In (c) and (d), the robustness of the relationship is shown by comparing a constant light extinction coefficient (0.36) with a coefficient that ranges linearly with spacing from 0.5 at 2.1 m² tree⁻¹ to 0.3 at 44.0 m² tree⁻¹

actual efficiency of photosynthesis could differ with spacing (resulting from greater water loss if open-grown canopies are coupled more tightly with winds and dry air), with lower leaf photosynthesis per unit of light intercepted at wider spacings.

Discussion

Both the classic block design and Nelder design for *Eucalyptus dunnii* would lead to the same operational decision about spacing of trees. The Nelder took up about half of the ground area required for the replicated block experiment, and the lower overall cost would allow for investing in several true replicates across the geographic range where spacing decisions would be applied. In most cases, spacing trials provide information on relative performance of trees; solid information on actual growth rates would depend on inventory plots spanning the geographic range of interest. These considerations combine to indicate that adopting a classic block design (replicated within a single site) should be considered only after clear justification of expected benefits relative to the simpler, cheaper designs (such as Nelder fans; Panetsos 1980, Salminen and Varmola 1993). For example, one such justification would be a study designed to examine effects of spacing on belowground production; Nelder designs might not be suitable for soil CO_2 efflux measurements (Giardina and Ryan 2002).

Experiments are typically designed to answer a well-defined question that is important at the present moment, but many experiments may provide opportunities for testing ideas that arise after the experiment begins. For example, these spacing trials were not designed initially to examine the production ecology factors that led to differences among spacings; the goals were simply to examine empirical growth and yield patterns. The addition of leaf area assessments at the end of the experiment for the clonal *Eucalyptus* Nelder design showed up to two-fold differences in efficiency of light use among clones (data not shown), pointing to great opportunities for future investigations of photosynthate allocation (particularly belowground production) and total light use efficiency (leaf photosynthesis per unit of light interception).

Forestry has a strong tradition of replicating treatments within single stands, for little or no apparent reason. While replication within a site allows differences among treatments to be analysed statistically, the population of inference is so small (a single stand) that the extra cost of replication is probably not justified (Binkley 2008). Most forest research questions are asked of large populations of interest, typically spanning geographic gradients of tens to thousands of square kilometres. A single site could provide insights on responses across huge areas only if the processes of interest are strongly independent of all the factors that differ across landscapes. Questions with answers that might vary with soils, climate, genotypes and management factors can only be examined statistically by replicating treatments broadly enough to capture major covarying factors. For example, another Nelder experiment at a site in Bahia, Brazil, showed greater sensitivity of trees to droughts near the centre of the Nelder plot than in the middle or outer portions of the plot (JLS unpublished data); this interaction of drought, spacing and growth was not apparent in the present study where water supply did not limit tree growth. Broader replication across the real populations of interest may seem daunting, but repeating treatments in a single stand simply cannot address patterns that would develop across large populations of interest. Nelder designs offer a compact, simple approach that may be particularly useful for developing insights on the effects of spacing when new areas are first brought into forest plantation management, when new genotypes are introduced, and when major innovations in silviculture are developed (Gonçalves et al. 2008).

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