ANALYTICAL METHODS TO AID INTERPRETATION OF THINNING EXPERIMENTS

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ABSTRACT

Thinning experiments are difficult to analyse thoroughly. Problems arise because different densities are deliberately created at the outset of the trial. Multiple measures, usually unevenly spaced in time, are subsequently obtained from the experiment. Consequently, analyses of variance are essentially irrelevant because of the very nature of the treatments, and covariance is compromised in that post-thinning covariates will be strongly correlated with treatments.

Efficient analyses can be obtained, however, by modelling each plot through time by use of sigmoid functions or orthogonal polynomials, then analysing the respective coefficients by ANOVA or discriminant techniques.

These latter ideas were applied to a dataset obtained from a *Pinus radiata* D.Don thinning experiment in the Northland region of New Zealand, where stocking densities of 200, 350, 500, and 1200 stems/ha were established in four randomised blocks. Basal area and mean top-height measures from ages 5 to 11 were summarised by orthogonal coefficients, but only after the raw data were adjusted by covariance, using pre-thinning basal area per hectare as a covariate. A canonical discriminant analysis isolated the 200 stems/ha blocks as having lower growth in both basal area and mean top-height development. From a sample of sectionally measured trees, it was established that the 200 stems/ha blocks also had significantly lower stand form-factors.

These results suggest design of thinning experiments could be enhanced by blocking the experimental plots with respect to initial growing stock, prior to any treatment.

Keywords: thinning experiments; multivariate methods; analytical considerations; *Pinus radiata*.

INTRODUCTION

A common type of forest field experiment is that concerned with thinning or spacing (*see*, for example, Cromer & Pawsey 1957; Hamilton 1976; Wiley & Zeide 1988; Woollons & Whyte 1989; Buford 1991). Typically, four or five residual stockings are created, usually at an early age, by waste or production thinning and the performance of these treatments is monitored over some decades by periodic remeasurement of the experimental plots. Alternatively, plots are planted at different spacings (for example, 2×2 m, 2×3 m), and then likewise followed through time. In either type of trial, later-age thinnings may or may not be considered.

These series of replicated experimental plots, comprising different stocking densities, potentially allow a researcher to contrast through time the respective yield trajectories as measured by, for example, basal area per hactare, mean top-height, or live stems per hectare. Other variables may include tree shape and branch development. Physical measurement or estimation of these may be annual or periodic—that is, the intervals between measurements may or may not be constant.

Analysis of these measurements and results is not, however, always straightforward. In this contribution, we substantiate this view and address the problem by describing the procedures used to examine data obtained from a thinning experiment in Northland, New Zealand. Problems met when analysing such trials are discussed, and the ramifications for experimental design of thinning experiments are outlined.

PROBLEMS IN ANALYSES: A SUGGESTED SOLUTION

At first inspection, it might be assumed analyses of variance or covariance, using yields at chosen time periods, will provide a satisfactory analysis, but this is not so. *A priori*, the experimental treatments are (deliberately) set at contrasting tree densities and so future basal area per hectare, for instance, must be distinct between treatments; significance testing in this respect is therefore almost irrelevant. Covariance analysis of post-thinning data is also compromised, in that the covariate (initial basal area or mean top height, for example) is strongly correlated with treatments. In any event, where many measures are available over time, these approaches become cumbersome and repetitive, and limiting examination to, say, the latest measurement, is inefficient as it does not utilise all available data.

The data structure outlined above is symptomatic of a repeated measures design (RMD) (Winer 1971), but the likelihood of the presence of many (say >10) re-measurements, probably at uneven intervals, makes a standard RMD analysis difficult. A satisfactory and thorough exploration of the data, however, may be achieved as follows:

(1) Model **each** plot sequence by a suitable yield-time function. For data over an appreciable age range, a sigmoid function is relevant; for shorter data-sets, it is sufficient to express the data in terms of linear, quadratic, and cubic coefficients, through orthogonal polynomials (Draper & Smith 1981). If uneven time intervals are present, calculation of the coefficients is still straightforward, although protracted without a computer routine (Carmer & Seif 1963).

Orthogonal polynomials are an efficient way of studying the response of a variable to levels of a factor, when replicated data are available. They are probably most frequently employed in analyses of variance, but can be used simply as summary statistics. In general, the linear coefficient represents a straight-line relationship, while the quadratic and cubic terms depict measures of curvature. Utilised in a thinning experiment analysis, the linear coefficient describes the slope of a yield curve averaged over time— that is, a measure of periodic annual increment. The quadratic coefficient largely represents growth rate or increment. The cubic term probably describes a familiar sigmoidal curve.

(2) Analyse the sigmoidal function or orthogonal coefficients singly and jointly through univariate and multivariate analyses of variance. Further insight may be obtained through a canonical analysis of the coefficients to discriminate between thinning treatments. Differences in yield paths can be demonstrated by calculating generalised squared distances, and plotting canonical scores resultant from the first two canonical variables (if significant).

EXPERIMENTAL

These points can be illustrated by an examination of data from a thinning trial at Forsyth Downs, Mangakahia District of Cater Holt Harvey Forests Ltd, in the Northland region of New Zealand. The experimental area was at an altitude ranging between 350 and 385 m, on Waimatenui clay soils. It had a predominantly north-east aspect, slight to moderate topography between 5° and 15°, with an average rainfall of 1180 mm/annum (207 rain days).

Past vegetation was predominantly grass with areas of scrub, but earlier land use had been pastoral. Pre-planting operations included the felling of scattered scrub species together with intensive grazing. The area was planted in mid-1982 at 1660 stems/ha at a spacing of 2×3 m with *Pinus radiata* seedlings grown from "climbing select" seed (GF7). After planting, the area was spot sprayed with Velpar for grass control, and fertiliser (elemental phosphorus as superphosphate) was applied by hand at 10 g/tree.

In 1987 (at age 5) sixteen 0.4-ha plots were established, with an inner measurement area of 0.1 ha. These were arranged in four randomised complete blocks, based on proximity. Four residual stockings were imposed, consisting of 1200, 500, 350, and 200 stems/ha. Prior to thinning, the diameters at breast height (1.4 m) of all plot trees were measured (residuals plus thinnings). Selection of trees for thinning in the 200, 350, and 500 stem/ha treatments was undertaken largely on tree size, but with some recognition of form. Thinning in the 1200 stems/ha treatment, conversely, was done mechanically (without selection), in an attempt to simulate initial stocking rates current at the time of the trial installation.

Diameter at breast height and tree height were measured annually for all experimental trees and plots up to 1993 (age 11). Mortality in the experiment over the period was negligible.

In late 1991 (age 9) three trees in each plot (chosen randomly over the diameter range) were intensively sampled for sectional bole and branch measurements. Underbark diameters within internodes were obtained by callipers and bark-gauge to approximately three-quarters of total height; usually between 15 and 20 diameter measurements were taken over 8–9 m. Total stem volume (underbark) was estimated for each tree, by summation of successive frustra, assuming a conoid as the volumetric shape.

ANALYSES OF TRIAL DATA

Preliminary analyses revealed a strong (linear) relationship between pre-thinned total basal area per hectare and subsequent residual basal area or mean top-height, suggestive of variable productivity within the experimental plots. Accordingly, the basal area per hectare and mean top height of each plot were adjusted through covariance using a separate coefficient for each year of growth. The association was especially (and logically) significant soon after thinning ($p < 0.0001$) for basal area, becoming weaker ($p < 0.05$) by age 11 (1993). Mean top height required adjustment until age 9 (significant at least at the 5% level). Adjusted and raw values for mean top height and net basal area per hectare over 1987–93 are given in Table 1. The adjusted basal area yields are illustrated over time for the respective treatments in Fig. 1.

TABLE 1–Mean top-height and basal area data (1987–93)

	Stocking (stems/ha)							
	200		350		500		1200	
	Raw	Adj	Raw	Adj	Raw	Adj	Raw	Adj
Mean top height (m)								
1987*	8.2		8.4		8.4		8.3	
1987	7.9	8.8	8.3	7.9	8.4	7.8	8.3	8.4
1988	8.9	9.7	10.1	9.8	10.2	9.8	9.9	9.9
1989	10.2	10.6	11.5	11.3	11.8	11.5	11.6	11.7
1990	11.9	12.5	13.8	13.5	14.0	13.6	13.8	13.9
1991	13.6	14.0	15.3	15.1	15.3	15.1	15.6	15.7
1992	16.0	16.0	17.5	17.5	18.2	18.2	17.7	17.7
1993	17.2	17.2	19.2	19.2	19.8	19.8	19.4	19.4
Basal area/ha (m^2)								
1987*	17.2		21.8		22.3		19.6	
1987	3.3	4.9	6.6	5.8	9.3	8.3	14.5	14.6
1988	6.2	8.4	11.8	10.8	15.5	14.2	22.5	22.7
1989	10.0	12.9	18.4	17.0	22.7	20.9	29.8	30.0
1990	14.0	16.9	24.4	23.0	28.6	26.8	35.8	36.1
1991	18.0	20.9	29.9	28.5	34.1	32.3	41.4	41.6
1992	22.0	25.1	35.1	33.6	39.7	37.8	47.1	47.2
1993	25.5	28.3	39.3	38.0	44.1	42.4	51.3	51.6

* Pre-thinning figures

These data strongly suggested different yield paths for the four treatments, both in basal area per hectare and in mean top-height development. To test these hypotheses, each plot was modelled in time, by expressing its annual measurements of basal area and mean top-height in terms of linear, quadratic, and cubic orthogonal polynomials (Draper & Smith 1981, p.273). (With only seven early-age measurements available, fitting of a sigmoid function was not really practical.)

Individual analyses of variance for basal area per hectare gave strongly significant ($p < 0.005$) differences for all three components and a joint analysis was significant at the 0.0001 level (Wilk's criterion). A canonical discriminant analysis confirmed two canonical axes were justified ($p > 0.0081$) which, however, accounted for 99.5% of the variation, and the resultant discriminant function correctly ascribed 15 of the 16 values to the original

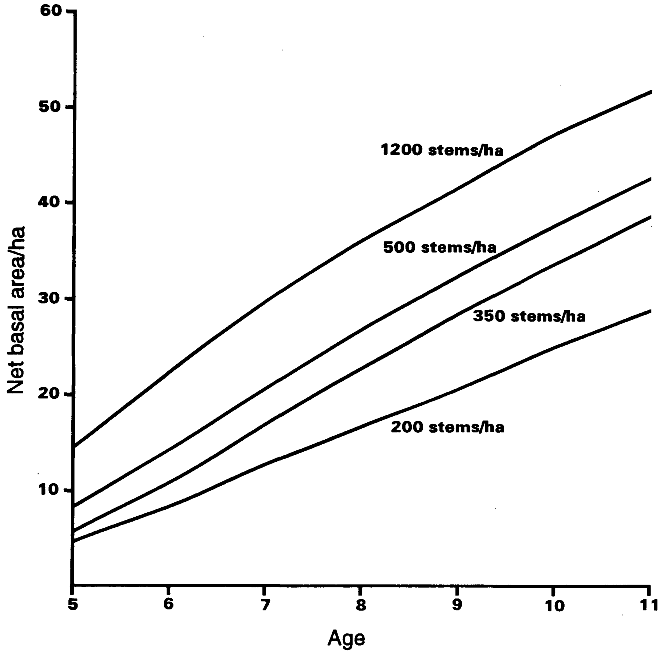

FIG. 1–Basal area per hectare yields for the four stockings.

treatments. Mean orthogonal coefficient values, squared distances (Manly 1986, p.42), and the first two canonical coefficient values for the four treatments are summarised in Table 2; canonical scores and 95% confidence zones (Mardia *et al* 1980, p.432) are depicted in Fig. 2.

Analyses of variance for the mean top-height coefficients gave significant ($p < 0.01$) differences to the linear coefficient, but not to any other component. Multivariate analyses gave no further insight. The mean linear coefficients are given in Table 2.

The intensively measured trees (12 per treatment) were analysed for differences in tree form-factor (f), defined as:

$$f = v/(g \times h)$$

where

v = tree volume
g = tree basal area, at 1.4 m
h = total tree height.

An analysis of covariance, using initial (1987) diameter at breast height squared as a covariate, gave significant ($p < 0.03$) differences for 1991. The estimated mean form-factors for the four stockings are given in Table 3.

RESULTS AND DISCUSSION

A major result is the influence of pre-thinning basal-area on subsequent growth. While not unexpected from a silvicultural stand-point, failure to allow for this effect in this experiment would have led to markedly biased estimates of yield for the four stockings. By

TABLE 2–Summary statistics for basal area and mean top-height analyses

Basal area/ha

Stocking (stems/ha)	Orthogonal coefficients Linear	s.e.	Quad.	s.e.	Cubic	s.e.
200	112	17.9	–2.7	2.1	–1.3	0.7
350	153	13.7	–9.5	6.0	–2.1	0.5
500	161	3.7	–13.4	8.7	–0.9	0.5
1200	172	12.6	–28.6	7.1	0.6	0.6

	Generalised squared distances 200	350	500	1200
200		13.3	15.9	38.5
350			5.0	25.7
500				9.4
1200				

Mean top-height

	Linear orthogonal coefficients	s.e.
200	40.9	3.4
350	53.7	4.4
500	56.4	6.3
1200	52.4	5.0

Canonical coefficients

$$Z_1 = 0.689X_{\text{lin}} - 0.302X_{\text{quad}} + 0.543X_{\text{cub}}$$
$$Z_2 = 0.550X_{\text{lin}} - 0.217X_{\text{quad}} - 0.835X_{\text{cub}}$$

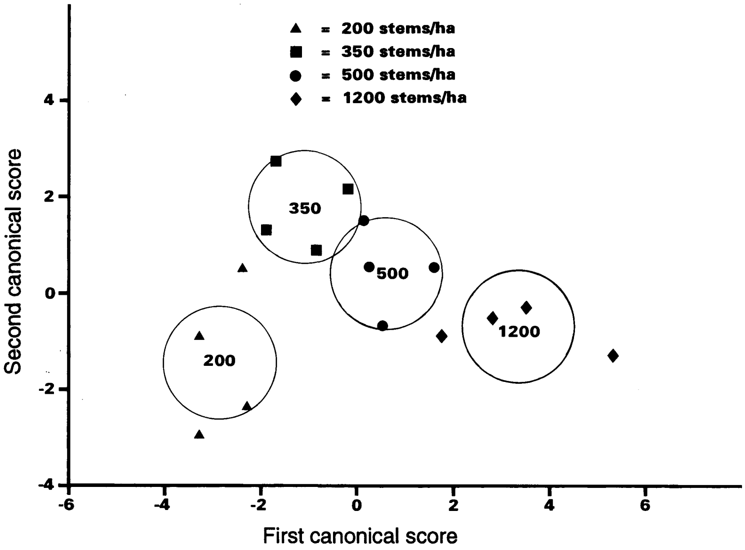

FIG. 2–Canonical score plottings for the four stockings.

TABLE 3–Stand form-factors (f)

Stems/ha	f	s.e.
200	0.338	
350	0.368	0.0079
500	0.367	
1200	0.356	

chance, the randomisation process employed at the initiation of the experiment allocated three of the five smallest (in standing basal area) plots to the 200 stems/ha treatment. Thus, the observed yields for this stocking treatment would have been under-predicted at age 11 by 2.8 m^2/ha, equivalent to an 11% bias.

The use of orthogonal polynomial coefficients neatly summarised the growth of plots at the four stockings, in lieu of a suitable sigmoid function which would require longer-term data to secure adequate definition. Moreover, all data available to date were utilised, which is better than limiting analyses to examination of yields at one chosen age. The 200 stems/ha treatment was characterised by a linear polynomial coefficient significantly lower than the 350 and 500 stems/ha ones, indicative of lower growth. Woollons & Whyte (1989 and Whyte & Woollons (1990) reported similar results in three thinning experiments in Kaingaroa Forest in the central North Island. Growth in the 1200 stems/ha treatment was also retarded in comparison with 350 and 500 stems/ha (Table 2) in the sense that, while it had the highest periodic annual increment over ages 5 to 11, an appreciably larger quadratic coefficient suggests peak growth had already occurred, and catabolic decline was becoming dominant.

Utilised jointly in a canonical analysis, the orthogonal polynomials efficiently highlighted the significant differences in the treatment's growth paths, through plottings of mean scores of the first two canonical variates, and associated 95% confidence zones (Fig. 2). The coefficients are given in Table 2. Interpretation of canonical variables is always subjective, but the dominance of the linear coefficient in the first variate was synonymous with average growth, implying a measure of yield. The second canonical variate was influenced largely by the cubic coefficient, which may depict growth rate.

The relationship between mean top-height and pre-thinning basal area was less marked, becoming independent by age 9. Nevertheless, covariance adjustment (*see* Table 1) altered early mean top-height estimates by up to 0.9 m, again equivalent to an 11% bias. The yield paths of mean top-height are simpler to model than basal area, the linear orthogonal coefficients alone sufficing to summarise the treatments. From Table 1, the 200 stems/ha treatment emerged 2 m lower in top-height development by age 11 than plots at higher stocking densities.

With lesser basal area and mean top-height development, it is perhaps inevitable that the 200 stems/ha plots should exhibit a significantly lower form-factor. How this difference in shape will behave in later years is conjecture, but already tree volumes from the 200 stems/ha regime at age 9, estimated by a two-dimensional volume function, are likely to be over-estimated by 8%.

Results reported here have considerable ramifications for the design and maintenance of thinning experiments, particularly for those established some years after planting. The evidence presented conclusively demonstrates that standing growing stock before thinning can partially determine subsequent growth of residual stems for at least 6 years after thinning. It thus becomes critical to measure all stems in an experimental plot, **prior** to thinning. While covariance analysis represents a successful technique to help remove possible bias in basal area or top-height resulting from randomisation of treatments, it is not a panacea. This experiment is perhaps unusual or unlucky in that one treatment received a preponderance of plots with small stock. To avoid this in future, blocking with respect to initial plot growing stock is strongly recommended, as utilised by Sutton & West (1980) and proposed by Andrew (1984). Historically, this is usually carried out with respect to plot proximity, which unfortunately is normally not effective (Woollons 1980, 1985). The suggestion gains further credence when comparison of the respective stand-tables is contemplated. We have not yet analysed in any depth the diameter distributions in treatments in this experiment; changes in ranking within stockings are still evident. Later on, however, we face a problem in that the 200 stems/ha treatment is unfairly represented, and this difficulty will not be easily removed by covariance analysis.

CONCLUSIONS

Analyses carried out after 6 years of measurement of a thinning experiment established that:

(1) Measurements of growing stock in an experimental plot before thinning can be strongly related to subsequent residual basal area and mean top-height, up to 6 years after thinning. In this event, observed plot yields need to be adjusted by covariance techniques to eliminate bias.

(2) When treatment yield paths comprise only a few measurements, orthogonal polynomial coefficients represent convenient statistics to summarise the data. Used jointly in discriminant canonical analyses, the coefficients could sensitively distinguish between yield trajectories of residual stockings in the 200 stems/ha treatment.

(3) Utilised in this manner, early data from a Northland thinning experiment showed that residual stockings of 200 stems/ha resulted in slower retarded growth in basal area and mean top-height development than with higher stocking densities. Tree form-factors were significantly lower.

(4) Growing stock in the total plot should always be measured before thinning when long-term thinning studies are being installed. Consideration should be given to blocking experimental units with respect to initial yield rather than to proximity.

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