HEIGHT GROWTH OF *PINUS RADIATA* AS AFFECTED BY STOCKING

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(Received for publication 30 November 1994; Revision 12 June 1995)

ABSTRACT

Results from 29 semi-mature trials of New Zealand *Pinus radiata* D.Don indicate that height growth is positively correlated with final-crop stocking in certain circumstances, and where stockings are less than 800 stems/ha (higher stockings were not analysed). A subsidiary dataset, with ages from planting to 7 years, gave results that confirmed these. Twelve of the trials demonstrated a significant ($p<0.05$) decrease in annual height increment with a reduction in stocking. For these trials there was an average height loss of 0.13 m/year after thinning to final stockings, or approximately 2 m over one typical rotation, for every halving in stocking. One possibility is that this effect is due to wind: lower stockings incur greater wind turbulence, which reduces height growth.

In order to standardise descriptions of stand height, a new equation was calculated to predict Mean Top Height from Predominant Mean Height.

Keywords: stocking; final stocking; height; height growth; wind; thigmomorphogenesis; *Pinus radiata.*

INTRODUCTION

The conventional belief is that tree stocking has little effect on height growth. The concept of "site index", for example, assumes that the height growth of a stand of trees is determined by environmental factors, and not by the silvicultural regime. Regime comparisons, including final-stocking comparisons, are usually simulated in computer models using site index as a constant for any given site. Only one New Zealand growth model, EARLY (West *et al.* 1982), contains an adjustment factor for height at low stockings. In this model, height growth is dependent on green crown length per hectare, which can be reduced by a combination of severe pruning or low stockings.

Most previous work on the effect of stocking on height growth has been carried out overseas with species other than *P. radiata*. Studies involving *P. sylvestris* L. (Scots pine), *Picea sitchensis* (Sitka spruce), *P. abies* (L.) Karsten (Norway spruce), *Larix decidua* Miller (European larch), *L. kaempferi* (Lamb.) Carrière (Japanese larch), and *Pseudotsuga menziesii* (Mirb.) Franco (Douglas-fir) by Hamilton & Christie (1974) demonstrated a height decline with stocking, but most work (e.g., Lynch 1958; Hamilton 1981; Kirkpatrick *et al.* 1981;

Rollinson 1988) showed no significant trend. Hocker (1979, pp.112–3) summarised the situation:

> "Height growth is not too greatly affected by stand density ... except that height growth may be affected where the stands are near the extremes of stocking. ... The trees will be shorter in both the overstocked or understocked stands than will trees in well-stocked stands".

Indeed, Lanner (1985) made the strong statement that

> "It is almost axiomatic that height growth of canopy trees is insensitive to initial spacing, and to the changes in spacing that follow the thinning of stands".

However, the lowest stocking rates quoted in overseas studies are higher than those commonly adopted by forest managers in New Zealand.

This study used data collected from trials throughout New Zealand to test if height is significantly affected by stocking at the range of stockings commonly encountered.

DATASETS AND METHODS

Trial Descriptions

The main dataset

For the main dataset (Table 1a), the Permanent Sample Plot (PSP) System (Pilaar & Dunlop 1990) was searched for trials with contrasts in stocking rates over a time period that could be expected to show a height difference (5 years). Only trials that met the following criteria were selected:

(a) Annual data available for 4.5 years or more after the stocking differential was established;

(b) Treatments replicated twice or more;

(c) Two or more stocking treatments covering a range from <150 to >400 stems/ha;

(d) Reliable height measurements, i.e., <10% trees with lean or broken tops.

Plots with final stockings greater than 800 stems/ha were excluded from the analysis, since natural suppression-induced mortality would have caused changes in stocking rates and would have confounded results by changing the stocking level.

It is difficult to compare the stocking of two trials for a prolonged period of time because, in any stand of trees, the stocking generally declines with age, either through deliberate thinning or through natural mortality caused by disease, suppression, or wind damage. Stocking comparisons are simplified after the final thinning (which often occurs early in the rotation in New Zealand), unless natural mortality is severe. If stocking had declined by more than 10% after the time of final thinning, the affected plot was ignored.

Heights were analysed at two ages only for each trial. "Initial age" was defined as the earliest measurement available after final thinning. "Final age" was defined as the most recent available measurement.

The subsidiary datsets

One trial (Tikitere) in the main dataset was scrutinised more closely. In-depth analysis of this trial (commonly called the Tikitere Agroforestry Trial) was considered useful, as it yielded a very comprehensive dataset, and has been intensively managed and monitored

TABLE 1a—Description of trials used in the main study

Forest	Trial No.	Selection ratio*	Number of plots	Initial age	Final age	Site index†	Min. stems/ha	Max. stems/ha	Plot size‡	Slope (°)	Altitude (m a.s.l.)
Whatawhata	AK 465	S	12	8.5	19.7	30.7	83	400	A	25	180
Tairua	AK 1025/1	S	9	6.0	12.0	24.9	48	400	B	6	100
Aupouri 1	AK 1025/2	S	10	9.0	15.0	22.7	50	601	B	0	50
Aupouri 2	AK 1025/3	S	10	10.0	16.0	23.9	50	601	B	0	50
Woodhill	AK 1056	N	17	11.1	16.9	24.1	90	700	D	0	20
Waimate	CY 588/1	S	10	8.1	14.1	26.1	48	601	B	40	400
Balmoral	CY 588/2	S	8	11.1	17.0	16.4	50	400	B	0	245
Okuku	CY 588/3	S	8	10.1	16.0	23.4	48	400	B	30	420
Hanmer	CY 588/4	S	8	7.0	12.1	24.1	45	400	B	0	366
Eyrewell	CY 597	N	17	11.0	17.0	20.6	95	600	D	0	180
Golden Downs 1	NN 278	N	12	14.0	23.6	27.7	111	420	C	30	403
Golden Downs 2	NN 529	N	17	11.0	17.0	26.9	90	675	A	26	670
Tikitere	RO 382	S	16	7.9	19.0	28.4	46	400	A	0	383
Kaingaroa (South)	RO 589/1	N	7	10.0	25.0	23.6	150	350	E	0	597
Kaingaroa (Central)	RO 589/2	N	16	9.0	26.0	28.8	117	383	E	5	520
Kaingaroa (North)	RO 589/3	N	7	7.1	24.0	30.5	150	350	E	5	440
Waimihia	RO 590	N	32	6.5	17.2	29.6	115	683	E	0	488
Kaingaroa 1	RO 680	N	10	10.7	30.0	30.0	99	395	F	0	542
Kaingaroa 2	RO 1891/1	S	13	7.5	12.0	28.3	87	400	A	0	550
Kaingaroa 3	RO 1891/2	S	12	7.3	12.0	28.4	87	400	A	0	550
Rotoehu	RO 2067	S	10	7.0	13.0	34.4	50	600	B	5	171
Kaingaroa	RO 2098	S	15	11.0	16.6	30.9	100	625	D	0	560
Otago Coast 1	SD 474	S	17	9.3	16.6	21.6	90	500	C	12	266
Otago Coast 2	SD 669	N	9	8.1	14.0	24.4	70	230	A	20	140
Gwavas 1	WN 216	N	6	9.7	21.7	29.5	99	198	E	15	488
Gwavas 2	WN 226	N	17	12.2	22.0	25.2	198	758	C	0	518
Ngaumu	WN 227	N	4	23.2	32.0	27.0	109	296	F	15	237
Glengarry	WN 286	N	26	7.7	15.2	30.6	120	380	F	17	319
Awahahonu	WN 368	S	6	9.0	15.0	26.8	48	200	C	3	450
Mean			12.4	9.66	18.20	26.53	87.69	460.2		8.8	335.3
S.d.			6.1	3.21	5.33	3.79	37.77	153.2		11.8	185.7

* Selection ratio. S = where an attempt was made to maintain a standardised ratio of pre-thinning to post-thinning stocking, across all treatments; N = where this was not done. Constant selection ratios are achieved either by planting at a range of stockings, or by mechanical thinning prior to selection thinning.

† Site index here refers to the mean of the predicted site index for each stocking in the trial, using the most appropriate height-age curve for the region, and the PSP measurements closest to age 20.

‡ Plot size. A = 0.8–12 ha; B = 0.2 ha (high stockings) to 1 ha (low stockings); C = 0.6–0.7 ha; D = 0.23 ha; E = 0.2 ha; F = 0.04–0.15 ha. "Plot size" includes the area of the surrounds.

from the time of planting. Each treatment was planted at five times the final stocking, thinned to 2½ times final stocking at age 3, to double the final stocking at age 4; to 1½ times final stocking at age 6–7, and to final stocking at age 8.

There were four final-stocking treatments: 400, 200, 100, and 50 stems/ha. These were replicated four times, blocked by aspect and slope. Each replicate comprised 2.0 ha, with 28-m surrounds, and contained four measurement plots of 10 trees. Wind damage resulted in top breakage in a number of trees, especially in the low stockings (Knowles & Paton 1989). To check that the observed height reduction was not the result of this wind damage, the height of every tree in every plot was measured in 1992 and only trees with no visible top breakage have subsequently been used to estimate height.

An independent dataset of five trials was used to examine stand behaviour at ages less than 7 years (Table 1b). These trials were established to measure the performance of several *Pinus radiata* breeds at a range of initial spacings from 200 to 1550 stems/ha.

TABLE 1b—Description of trials used to assess early stand behaviour

Forest	Trial No.	Stand age
Woodhill	FR 7	4.3
Kaingaroa	FR 9	6.8
Tikokino	FR 57	5.6
Blenheim	FR 11	5.7
Otago Coast	FR 12	6.9

Height Measurement

It is normal practice during routine annual re-measurement of permanent sample plots to record heights of only a sample of trees because height data are time-consuming to collect. Several sampling strategies are used. The most common is to sample across a range of diameters at breast height (dbh), in order to obtain a Petterson equation linking diameter and height. This is then used to calculate the Mean Top Height (MTH), defined as the predicted mean height of the 100 stems/ha with the largest dbh (Burkhart & Tennent 1977). Alternatively, the tallest tree in each 0.01-ha plot is recorded. The mean of such trees (usually a minimum of six) is known as the Predominant Mean Height (PMH).

Our main dataset included results from trials in which MTH, PMH, or both had been assessed. MTH is approximately equal to PMH, but for the purposes of this study it was desirable for all height estimates to be on the same basis. In nine trials (Tairua, Aupouri 1 and 2, Rotoehu, Awahahonu, Waimate, Balmoral, Okuku, and Hanmer) heights of every tree had been recorded, and these were used to generate a regression formula expressing PMH in terms of MTH. Site index and age did not affect the relationship, but stocking had a significant effect ($p = <0.05$). The equation giving the best fit was:

$$MTH = 0.394 + 0.982 * PMH - 0.00102 * stems/ha \quad (r^2=0.99) \qquad \ldots 1$$

with less bias in the residuals (*see* Appendices 1 and 2) than for the Burkhart & Tennent (1977) equation:

$$MTH = -0.3533 + 1.0179 * PMH \quad (r^2=0.99 \qquad \ldots 2$$

For the purposes of this study, another equation was generated to omit the stocking term:

$$MTH = 0.51 + 0.9587 * PMH \quad (r^2 =0.99) \qquad \ldots 3$$

Using Equation 3, all heights in the following trials were converted to MTH:

Kaingaroa (South), (Central), (North)
Kaingaroa 2 and 3
Waimihia—except ages 4 and 6
Gwavas 1 and 2
Ngaumu—age 32 only
Whatawhata

Statistical Analysis

Three measures of MTH growth were obtained for each plot. Mean annual height increment (MAI) corrected to a site index of 30 m was calculated for the initial and final height measurements using (MTH*30)/(age*SI), where SI is the site index averaged over all plots in each trial. Periodic annual height increment (PAI) was calculated using (Final MTH – Initial MTH)*30/((Final Age – Initial Age)*SI).

These variables were subjected to an analysis of variance (ANOVA) in which the following factors were fitted:

Trial (regarding trials as a blocking effect),
Stocking
Trial × Stocking interaction (to determine whether the effect of stocking on height varied between trials).

Stocking was tested both by using five stocking classes (0–100, 100–200, 200–300, 300–500, and 500–800 stems/ha) and by using the natural logarithm of stocking as a covariate. The natural logarithm transformation was used on the assumption that any stocking effect would be more marked at lower stockings. (A linear regression would imply that a stocking difference of 600–700 stems/ha could influence height as much as 100–200 stems/ha).

It appeared likely that any differences between trials might depend on whether a constant selection ratio had been maintained, and might also be influenced by plot size, with edge effects from neighbouring plots reducing the effect of stocking on height growth in smaller plots. The contributions to the Trial × Stocking interaction of these two factors as classified in Table 1 were therefore tested in the ANOVA.

For a more detailed view of individual trials, regressions of the two MAIs and PAI against the natural logarithm of stocking were obtained for each trial. The regression coefficients were examined against constant *v.* non-constant selection ratio, plot size, site index, elevation, and slope.

RESULTS AND DISCUSSION

Analysis of the Total Dataset

The ANOVA of the initial MTH*MAI*, final MTH*MAI*, and MTH*PAI* all showed highly significant stocking effects (Table 2). Although the interaction between trial and stocking was statistically significant for the PAI only when trials were classified by selection ratio (constant *v.* non-constant) or by plot size, both effects were found to interact significantly with stocking. However, the effect of plot size after first fitting selection ratio was not significant (except for initial MAI) and vice versa. This suggests that these effects are

TABLE 2—Summary ANOVA of initial and final MTH MAI and PAI

Source†	d.f.	Initial MAI (m/ha/yr)		Final MAI (m/ha/yr)		PAI (m/ha/yr)	
		SS	F-ratio	SS	F-ratio	SS	F-ratio
Trial	28	8.54	18.78**	1.84	5 **	13.43	32.61**
Stocking class	4	0.579	8.91**	0.691	13.15**	1.158	19.68**
Trial × Stocking	80	1.479	1.14	1.090	1.04	2.483	2.11**
SR × St	4	0.205	3.16*	0.313	5.95**	0.622	10.57**
(PS|SR) × St	18	0.540	1.85*	0.242	1.02	0.408	1.54
PS × St	18	0.709	2.42**	0.510	2.16**	0.926	3.49**
(SR|PS) × St	4	0.037	0.56	0.045	0.85	0.105	1.78
(Trial|SR+PS) × St	58	0.733	0.78	0.536	0.70	1.453	1.7 **
Error	248	4.03		3.26		3.62	
Trial	28	8.54	18.66**	1.84	5.28**	13.43	36.1 **
Log_e(Stocking)	1	0.58	35.78**	0.76	61.08**	1.12	84.57**
Trial × Log_e(Stocking)	28	0.55	1.20	0.51	1.46	2.14	5.74**
Error	303	4.95		3.77		4.00	

* Difference significant at p=0.05
** Difference significant at p=0.01
† St - stocking class
SR - selection ratio (*see* Table 1 for definition)
PS - plot size (*see* Table 1 for definition)

confounded. Most of the trials with constant selection ratios had large plots, whereas most of the other trials had small plots (Table 1).

When stocking was fitted to the ANOVA as a covariate, *log_e(Stocking)*, the variance explained was similar to that obtained using stocking classes. This indicated that, over the range of stockings in this dataset (50 to 700 stems/ha), the response of height to stocking closely approximated a logarithmic relationship.

The least-squares means for the stocking classes estimated from the ANOVA are shown separately for the constant and non-constant selection ratio trials in Fig. 1a and b. Height increment tended to be directly related to stocking but only in the trials with a constant selection ratio.

Analysis of Individual Trials

For each of the trials, the regression coefficient *b* (determining the slope of the regression line) was calculated for the linear relationships between the natural logarithm of successive doublings of stocking rate and (i) initial MTH*MAI*, (ii) final MTH*MAI*, and (iii) PAI*MAI* (Table 3). A positive value of *b* implied that height increment was directly related to stocking rate while a negative value indicated an inverse relationship. A positive value of *b* for the MTH*PAI*/stocking relationship implied that the height differential between stockings had increased since the initial measurement.

Although no effect of site index, elevation, or angle of ground slope was detected, a significant positive relationship between stocking and height was demonstrated for periodic annual increment (PAI) in 12 trials. Three trials showed a significant negative relationship with PAI. The apparent influence of selection ratio on the regression coefficient *b* was

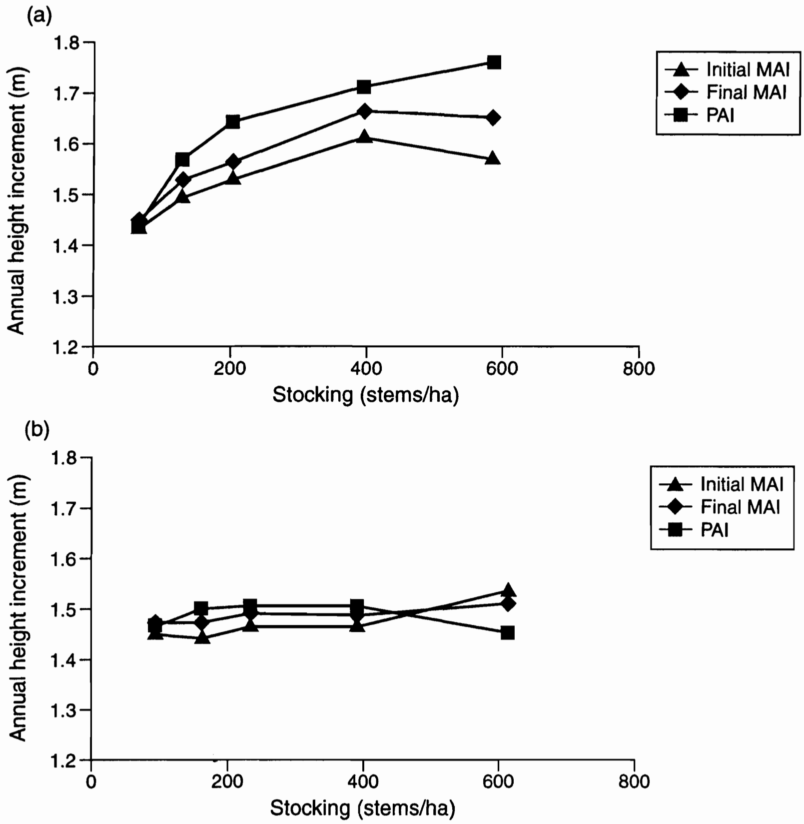

FIG. 1—Initial, final, and periodic mean annual increment of height for each stocking class for the trials (a) with a constant selection ratio and (b) without a constant selection ratio.

indicated by the position of trials in the list ranked in order of decreasing value of *b* for PAI. Most trials with a constant selection ratio appeared in the first half of the list.

The overall mean annual height increase associated with a doubling of stocking rate was 0.04 m. For trials with constant selection ratio only, the mean value was 0.10 m. Trials with the three largest plot size classes gave a mean value of 0.08 m. Trials with large plots and a constant selection ratio (the combination which closely represents the effect of varying final-crop stocking in a commercial plantation) had a mean value of 0.1 m.

At What Age Does the Stocking Effect Occur?

The Tikitere Agroforestry Trial exhibited a marked increase of height increment with stocking. The comparison of heights in 1993 (age 20) is given in Table 4.

Thinning intensity and timing were the same for each treatment, and therefore this trial could be used to examine if the observed height difference occurred early in the rotation, or whether it was associated with later growth. To do this, annual increment was calculated for each treatment and standardised by expression as a proportion of the increment in the 200

TABLE 3—Slope coefficients (*b*) for regression of different estimates of MTH on the natural logarithm of stocking rate. Trials are ranked in order of decreasing value of *b* for MTH*PAI*.

Trial	Selection ratio†	Initial Mean Annual Increment (m/year)			Final Mean Annual Increment (m/year)			Periodic Annual Increment (m/year)	
		Age	*b*‡	S.E.§	Age	*b*	S.E.	*b*	S.E.
Aupouri 1	S	13.3	0.011	0.025	20.5	0.085**	0.017	0.197**	0.017
Golden Downs 1	N	11.5	0.069	0.032	16.5	0.094**	0.02	0.147**	0.031
Tikitere	S	15.1	0.131**	0.022	23.1	0.134**	0.017	0.135**	0.016
Woodhill	N	6.8	0.001	0.036	16.4	0.046	0.025	0.134**	0.022
Rotoehu	S	11.5	0.002	0.009	16.5	0.061**	0.014	0.13**	0.025
Awahahonu	S	8.6	0.026	0.036	12.6	0.067*	0.019	0.127**	0.02
Kaingaroa 2	S	11.8	0.085	0.138	25.8	0.099	0.145	0.125**	0.039
Aupouri 2	S	8.9	0.056	0.031	18.7	0.082*	0.027	0.124*	0.048
Otago Coast 1	S	9.2	0.093	0.059	25.5	0.121**	0.038	0.117*	0.04
Okuku	S	23.9	0.022	0.016	31.5	0.055*	0.023	0.111*	0.044
Hanmer	S	10.5	0.039	0.024	24.5	0.066*	0.018	0.103**	0.019
Kaingaroa 3	S	7.5	0.107*	0.034	23.5	0.075**	0.01	0.07*	0.03
Balmoral	S	8.1	0.031	0.024	13.8	0.051*	0.014	0.088	0.044
Kaingaroa (North)	N	11.5	0.036	0.057	16.3	0.054	0.029	0.062	0.041
Kaingaroa	S	6.5	0.028	0.014	10.5	0.042**	0.012	0.061	0.03
Tairua	S	7.6	0.074	0.051	11.3	0.054	0.03	0.035	0.026
Kaingaroa (Central)	N	7.5	−0.016	0.014	10.6	0.008	0.018	0.021	0.027
Waimihia	N	11.6	0.024	0.014	15.5	0.025	0.016	0.017	0.026
Golden Downs 2	N	9.8	0.003	0.036	16.1	0.007	0.026	0.014	0.043
Whatawhata	S	9.5	0.112*	0.04	13.5	0.055	0.043	0.012	0.05
Kaingaroa (South)	N	11.6	0.014	0.05	16.5	0.013	0.031	0.012	0.047
Waimate	S	7.8	0.009	0.019	11.3	0.006	0.017	0.002	0.03
Glengarry	N	10.5	−0.005	0.061	14.5	0.026	0.05	−0.002	0.076
Otago Coast 2	N	7.9	0.007	0.084	18.5	−0.032	0.062	−0.006	0.074
Kaingaroa 1	N	7.5	0.055	0.035	11.5	0.015*	0.006	−0.008	0.024
Ngaumu	N	8.6	−0.025	0.039	12.5	−0.037	0.052	−0.071	0.088
Eyrewell	N	10.6	0.03	0.018	14.5	−0.02	0.01	−0.112**	0.028
Gwavas 2	N	9.5	0.124**	0.02	13.5	−0.003	0.017	−0.146**	0.027
Gwavas 1	N	10.7	0.079	0.096	20.9	−0.028	0.032	−0.289**	0.031
Mean		10.19	0.042		17.12	0.042		0.042	
S.d.			0.008			0.008		0.019	

† Selection ratio. S = where an attempt was made to maintain a standardised or constant ratio of pre-thinning to post-thinning stocking, across all treatments; N = where this was not done. Constant selection ratios are achieved either by planting at a range of stockings, or by mechnical thinning prior to selection thinning.

‡ Coefficient is derived from the slope of the regression of MTH on the natural logarithm of stocking, and is the increase in MTH increment (m/yr) corresponding to a doubling in stocking, standardised to site index 30 m to facilitate comparison between sites.

§ S.E. = Standard error of coefficient. Statistical significance of coefficient indicated as follows:
* Significant at p=0.05
** Significant at p=0.01

TABLE 4—Mean Top Height (MTH) at Tikitere for each stocking, at age 20

Nominal stocking (stems/ha)	Actual stocking (stems/ha)	MTH (m) or mean height*
50	47.2	25.4
100	95.0	27.6
200	193.8	30.1
400	385.0	33.5

* If stocking is less than 100 stems/ha, the mean of all heights is taken as MTH.

stems/ha treatment. In Fig. 2, this is termed "Relative Height Increment". If the relative height increment is greater than one, then height growth is superior to the 200 stems/ha treatment, and vice versa.

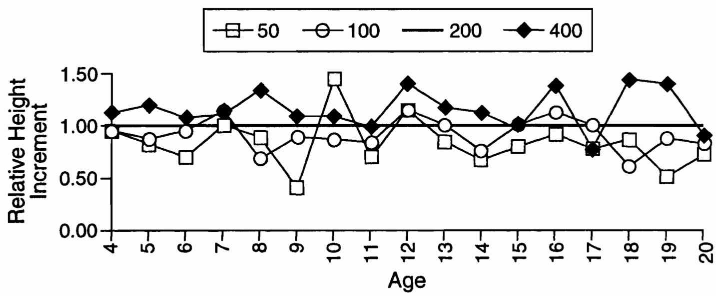

FIG. 2—Height growth at Tikitere relative to stocking, from age 4 to age 20

The height growth for 400 stems/ha was usually higher than for 200 stems/ha, and the growth for 50 and 100 stems/ha was generally lower. There were anomalous years where this was not so, where measurement error or variation in choice of sample trees could be implicated. The interesting observation is that there was no trend over time—the effect of stocking on height growth appeared to be operating to an equal extent at all ages.

The observation that increase in height increment with stocking rate starts at a very young age was supported by an independent dataset. A series of field trials established to measure the performance of several *P. radiata* breeds planted at a range of initial spacings offered the opportunity to examine if height growth is affected at an early age. Results averaged across all breeds (giving 6–8 replicates) of a range of initial (i.e., planted) stockings are given in Table 5. The early effect of stocking on height growth was clearly evident in the trend to taller trees with higher stockings, although the Woodhill data are anomalous at very high stockings.

Is the Observed Height Reduction an Artefact?

A possible source of bias is in plot area. If there are 20 trees per plot (as in many of the trials in this paper) a plot of 50 stems/ha will occupy 0.4 ha, whereas 600 stems/ha will occupy 0.033 ha. In any stand at a constant stocking, there will be differences in height growth due to microsite. The higher stockings sample a smaller proportion of these microsite differences, and can be expected to incorporate fewer large trees in situations where height differences vary on a scale of the same order of magnitude as plot size. On the other hand,

TABLE 5—Effect of initial stocking on MTH (m) at the time of the first pruning lift, in the early stand behaviour trials.

Initial stocking (stems/ha)	Woodhill FR7 4.3 years	Kaingaroa FR9 6.8 years	Tikokino FR57 5.6 years	Blenheim FR11 5.7 years	Otago Coast FR12 6.9 years	Mean of matched sets
200–300	n/a	6.5 a	6.5 a	6.5 a	6.5 a	6.59 a
450–550	7.1 a	7.3 b	7.1 ab	6.9 ab	7.1 ab	7.05 a
950–1050	7.8 a	7.3 b	7.4 b	7.6 ab	7.6 ab	7.53 b
1450–1550	7.5 a	7.8 c	7.3 b	8.2 b	8.0 b	7.73 b

Values with the same letter within each column are not significantly different at p=0.05. There was no stocking/site interaction and the means of the matched sets were compared using pooled within-site error.

some stocking trials have a constant area, but vary the number of trees per plot. Although the plot area is the same for these, there are a greater number of trees from which the "top height" trees can be selected in the higher stockings. In situations where there is great tree-to-tree variation in height, plots with lower stockings can be expected to sample fewer large trees. There is no method whereby stockings can be compared using sampling that is unbiased both from the perspective of sample area and from that of sample size.

Secondly, it is necessary to show that the observed height reduction with decreased stocking is genuine, rather than an artefact of the measurement system or calculation method. Several possible sources of bias have been identified. Mean Top Height is defined as "the mean height of the 100 stems/ha with the largest diameters". Since there is no proper height definition for stockings of less than 100 stems/ha, MTH for these treatments is taken to be the arithmetic mean of all "acceptable" trees. (Unacceptable trees are nearly always shorter, as a result of wind damage or other defect). In higher stockings, on the other hand, all measurements are used to generate a regression equation to estimate the MTH.

It is also necessary to ensure that stocking effects are not confounded with effects of selection ratio. Some trials had been thinned to their final stocking from a uniform initial stocking. Low final stockings would therefore have a higher selection ratio than high final stockings. If we assume that tree vigour was one criterion for selection, then one would expect the trees in a low final-stocking treatment to be inherently more vigorous than those in high stockings. If genetic factors are implicated in this superior vigour, it is possible that the advantage will persist to maturity. The South, Central, and North Kaingaroa trials, for example, showed no effect of stocking on height growth, and were thinned from a uniform initial stocking. It is possible that the selection advantages conferred on trees at low stockings counterbalanced smaller height increments and contributed to the net result described by Fig. 1b. Fifteen of the trials in this paper were part of a series in which stocking treatments were imposed on existing stands. For these trials, an attempt was made to maintain a constant selection ratio of 3:1 for the lower stockings (200, 100, and 50 stems/ha), but it was not possible to do the same for higher stockings.

It was possible to test the hypotheses that the observed effect is an artefact derived from the definition of Mean Top Height, or from a selection ratio effect. To do this, alternative definitions of height were employed for a sub-sample of the data. Eight trials were examined in detail. All trees in each trial had been measured for height, and they had been thinned to a final crop stocking from a common stocking within 6 months of the first measurement.

Estimates of height based on the following definitions were tested:

Mean of height of the 100 largest diameter stems/ha (i.e., conventional MTH);

Mean of heights of all trees;

Mean of height of the 30 largest diameter stems/ha;

Mean of height of the 50 largest diameter stems/ha;

Mean height of 10% largest diameter trees;

Mean height of 25% largest diameter trees;

Mean height of 50% largest diameter trees;

Predominant Mean Height.

These were regressed against the natural logarithm of the stocking, and the slope was tested for statistical significance (Table 6).

For most trials the slope of the regression line had a low value, statistically indistinguishable from zero, in the first year after a stocking differential was established. There was no evidence of an initial height difference due to stocking, or of a height difference attributable to selection ratio. At later ages, a significant effect of stocking on height was evident in most trials. It tended to increase with the interval between the establishment of the treatments and the date of measurement. The effect was present with all definitions of height, but appeared to be less common when a percentage measure was used. The accepted definition of Mean Top Height may therefore lend itself to a biased interpretation of Tables 2 and 3.

In a different approach, the degree of overlap in height distributions at different stockings was assessed. A comparison of heights of trees at 50 stems/ha with those at 400 stems/ha in the Tikitere trial showed that there was little overlap (Fig. 3). The majority of trees at 400 stems/ha were taller than the median tree at 50 stems/ha, and the tallest tree at 50 stems/ha was shorter than the modal tree at 400 stems/ha.

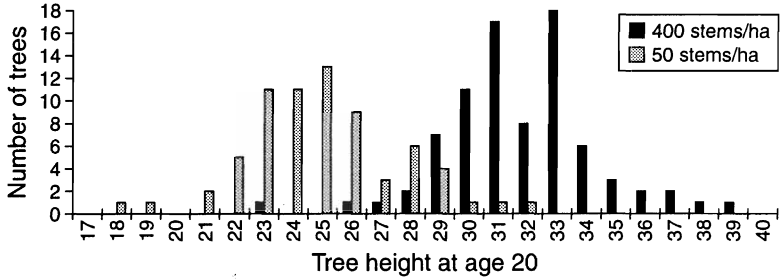

FIG. 3—Comparison of heights at Tikitere, at 50 stems/ha and at 400 stems/ha

A final point is the suggestion, made during review of this paper, that breakage by wind affects taller trees preferentially at lower stockings. In other words, the height sample in lower stockings is restricted to those short trees that have avoided wind damage, whereas the height sample in high stockings is a true indication of the potential height growth. The lack of overlap in Fig. 3 does not support this theory. Furthermore, it may not be of management importance to know whether trees are short because they have been broken, or if they are short because they merely have not grown tall.

TABLE 6—Examination of alternative methods of height estimation. Values are slope coefficients (*b*) for regression of different estimates of MTH on the natural logarithm of stocking rate.

Forest	Age	Method of estimating height							
		Mean	MTH 30	MTH 50	MTH 100	10% fattest	25% fattest	50% fattest	PMH
Tairua	6.0	0.13	0.26	0.41*	0.38	0.29	0.22	0.13	0.25
	7.0	0.18	0.38	0.58**	0.44	0.36	0.25	0.15	0.49
	8.0	0.22	0.60*	0.77**	0.62*	0.43	0.32	0.28	0.62*
	9.0	0.27	0.57*	0.74**	0.66*	0.48	0.29	0.27	0.64
	12.0	0.36	0.34	0.64*	0.54	0.42	0.23	0.09	0.74*
Aupouri 1	9.0	–0.06	-0.03	0.07	0.07	–0.17	–0.10	–0.08	0.21
	10.0	0.09	0.23	0.32**	0.21	–0.12	0.26	0.13	0.38*
	11.0	0.24	0.20	0.42**	0.41**	–0.02	0.18	0.19	0.60**
	12.0	0.38*	0.23	0.41*	0.54**	–0.08	0.23	0.35*	0.81**
	15.0	0.78**	0.61*	0.76**	0.97**	0.40	0.72**	0.77**	1.22**
Aupouri 2	10.0	0.01	0.07	0.28	0.44	–0.08	0.22	0.10	0.56**
	11.0	0.12	0.29	0.56	0.72**	0.27	0.37	0.22	0.75**
	12.0	0.33	0.53	0.65**	0.87**	0.54	0.57*	0.39	0.90**
	13.0	0.44	0.75*	0.91**	0.97**	0.86*	0.45	0.46	1.08**
	16.0	0.41	0.72	0.90**	1.05**	0.88*	0.76**	0.48	1.17**
Waimate	8.1	–0.30*	0.07	0.14	0.07	–0.13	–0.18	–0.20	0.15
	9.0	–0.26*	0.06	0.16	0.14	–0.21	–0.14	–0.12	0.22
	10.0	–0.28*	0.13	0.19	0.15	–0.23	–0.21	–0.11	0.25
	11.0	–0.24	0.12	0.21	0.17	–0.13	–0.19	–0.13	0.30
	14.1	-0.24	0.09	0.35	0.08	0.00	–0.34	–0.21	0.20
Balmoral	11.1	-0.18	0.17	0.29	0.19	0.04	–0.09	–0.09	0.18
	12.0	–0.17	0.15	0.31	0.25	0.03	–0.18	–0.14	0.21
	13.0	0.01	0.33	0.64*	0.38*	0.23	–0.03	0.16	0.41*
	14.0	0.03	0.18	0.40	0.41**	–0.07	–0.01	0.07	0.52**
	17.0	0.15	0.30	0.52*	0.47**	0.17	–0.05	0.16	0.69**
Okuku	10.1	0.00	0.12	0.42*	0.18	–0.07	–0.14	–0.23	0.33
	11.0	0.03	0.09	0.43	0.16	–0.16	–0.36	–0.22	0.32
	12.0	0.20	0.44	0.66*	0.31	0.09	–0.28	0.14	0.46*
	13.0	0.29	0.52	0.84*	0.62*	0.20	–0.03	0.11	0.77**
	16.0	0.32	0.50	0.87**	0.69*	0.24	–0.09	0.16	0.88**
Rotoehu	7.0	–0.22**	0.00	0.14	0.02	–0.14	–0.20**	–0.21**	0.21*
	8.0	0.03	0.40*	0.59**	0.29**	0.12	0.06	0.10	0.62**
	9.0	0.11	0.55*	0.68**	0.52**	0.30	0.26	0.24**	0.74**
	10.0	0.31**	0.74*	0.80**	0.68**	0.68*	0.45**	0.39**	0.98**
	13.0	0.35**	0.77*	0.97**	0.91**	0.55	0.49*	0.70**	1.12**
Awahahonu	9.0	0.05	0.09	0.22	0.22	0.01	–0.08	–0.03	n/a
	10.0	0.21	0.41	0.52	0.27	–0.20	0.03	0.01	0.40
	11.0	0.56**	0.74	1.10**	0.26	0.14	0.80	0.31	0.40
	12.0	0.36	0.46	0.81**	0.48	–0.36	–0.04	0.32	0.74*
	15.0	0.27	0.68	1.24**	0.89**	0.30	0.74*	0.02	1.16**

* Difference significant at p=0.05
** Difference significant at p=0.01

Is Wind Exposure Responsible for Reduced Height Growth at Low Stockings?

The data in Table 3 indicate that there is a clear correlation between stocking and height in many trials, but that in other trials no such effect is observed.

One explanation could be that differential wind effects were involved. Wind speeds are higher in stands at low stockings (Fraser 1964), and mechanical perturbation caused by the higher winds reduces cell elongation. Jacobs (1954) observed a mean height growth of 5.7 ft in 10 stayed *P. radiata* trees and 5.1 ft in 10 free-swaying trees (significant at $p = 0.05$). Telewski & Jaffe (1986a, b) provided data on height growth of trees with and without mechanical perturbation. Out of 23 half-sibs of *Pinus taeda* L. all but two exhibited an apparent or significant decrease in extension growth in response to mechanical perturbation. The decrease was associated with shorter tracheid lengths. The authors observed that

> "These data tend to support the thigmomorphogenetic theory which states that the anatomical, morphological and biomechanical changes that occur in response to mechanical perturbation appear to function in maintaining the structure of a tree in an environment where there is mechanical perturbation (i.e. wind)".

Examples supporting this theory were provided by Richter (1984) who produced evidence that buttress formation in *Quararibea asterolepis* developed as a response to wind, and Lawton (1982) who showed that the height growth of *Didymopanax pittieri* was reduced near ridgecrests as a result of exposure to wind.

Evidence of thigmomorphogenesis has been noted in trials with species other than trees, e.g., tomatoes (Heuchert & Mitchell 1983; Heuchert *et al.* 1983) and beans (Biro *et al.* 1980; Hunt & Jaffe 1980).

Larson (1965) supported the hypothesis of wind-induced reduction of height growth:

> "The reduction in height growth of trees exposed to strong wind is of common occurrence and has been well documented in the literature (Satoo 1962)".

He provided data to show that, in an experimental situtation, *Larix laricina* attained a substantially greater height increment under conditions of no wind than in wind.

Cremer *et al.* (1982) made the observation that

> "There is indirect evidence that the height growth of *P. radiata* can be markedly reduced at very low stockings, apparently as a result of increased exposure to wind".

Information has been collected on exposure at Tikitere under three stockings of trees and above open pasture (Table 7). The trend was the same for extreme wind runs and for each of the four seasons. The similarity of wind run in the 100 and 200 stems/ha stands has not been explained, but may relate to the fact that measurements were taken near the ground rather than at the level of the crown.

Data on the wind exposure of trials other than Tikitere are not available to test Cremer's hypothesis against the full dataset in this paper. Nevertheless, it is postulated that extreme height differences occur on windy sites, particularly where the treatment area is large. The Tikitere trial, for example, was situated in a windy location with low stocking treatments of sufficient size to enable wind to penetrate. The Kaingaroa South, Central, and North trials, in contrast, were well-replicated but located in the middle of Kaingaroa Forest where surrounding trees can offer substantial shelter.

TABLE 7—Annual average wind run at Tikitere (km/day) at 50 cm above ground (from Hawke & Wedderburn 1995)

Stocking (stems/ha)	Year 1982	1983	1984
Nil	143	161	125
100	80	97	61
200	87	97	60
400	25	36	32

These results emphasise that caution is necessary in interpreting the results of a single trial, or even several trials. Note that many of the trials investigated here were well replicated, and would withstand close scrutiny when examined in isolation. It is necessary to use a large dataset, and long periods of measurement, in order to investigate the universal significance of an observation.

The evidence in this dataset that height differences appeared to be more pronounced in larger plots gives some support to the "wind hypothesis". In small plots, the sheltering effects of neighbouring plots would be expected to mask any true stocking effects. However, it should be noted that in this dataset it was difficult to separate the effects of plot size and selection ratio. The evidence is not conclusive since no specific data on wind penetration at appropriate heights were available.

If subsequent work supports the hypothesis that *P. radiata* growing at low stockings experiences a height loss due to exposure effects, then adjustments should be made to height-age models, unless the site is sheltered. Depending on the level of exposure, site index should be adjusted downwards by up to 2 m for every 100 stems/ha drop in final-crop stocking below 400 stems/ha. Further work is required to obtain data that can shed light on the relationship between exposure to wind and height growth.

Does Early Trial History Influence the Effect of Stocking on Height Increment?

Stocking affects height growth only when there has been a constant selection ratio (Fig. 1a and b). If a range of final stockings is obtained from highly stocked stands by selecting the best trees, then there is likely to be little difference in height growth. Two explanations are possible:

(1) If the selection ratio is variable between treatments, this may imply that low stockings incur some advantage which offsets the inherent disadvantage of such stockings. For example, 100 stems/ha selected from 2000 stems/ha gives a selection ratio of 20:1 and the trees may be genetically superior to 400 stems/ha selected from 2000 stems/ha, with a selection ratio of only 5:1. On the other hand, there is no evidence (the "initial MAI" line in Fig. 1b) that an increased selection ratio has yielded a measurable height benefit to low stockings.

(2) The trials with a non-constant selection ratio have often been based on high initial stockings. For example, some were established in regenerated stands with initial stockings as high as 20 000 stems/ha. It is conceivable that this early history has been

retained as a "memory" in older trees, whereby a strategic decision to allocate resources to height growth in order to avoid overtopping is made in early years and retained thereafter.

Are There Other Explanations for the Observed Effect of Stocking on Height Growth Increment?

In the process of peer review, it was suggested that light direction may be responsible for influencing height growth. It might be expected that the well-known effects of light intensity on bud formation and internode elongation (*see* e.g., Zimmermann & Brown 1974, pp.626–9; Kramer & Kozlowski 1979) may account for increased height growth in densely stocked stands. The fact that the effect was statistically significant in only 12 of the 29 trials listed in Table 3 indicates that light intensity is not likely to be a major contributing factor.

CONCLUSIONS

Data from 29 trials indicated a loss in height growth at low stockings which, over a rotation period of 28 years, would average about 2 m for each halving of stocking.

Exposure to wind is suggested as a possible mechanism for this effect, and there is a substantial body of literature to support this view. On the other hand, the "wind hypothesis" is not supported by any statistical link between the stocking effect and slope or altitude, although an apparent plot area effect provides some circumstantial evidence. However, much of the variation in behaviour between trials can be explained by the presence or absence of a constant selection ratio at the time of thinning. One possible explanation for this is that a variable selection ratio confers advantages to low final stockings (in that they are selected from a proportionately larger number of trees) which counteracts any negative effects on height growth. Another is that high stockings in the early years of a stand's history will influence its subsequent behaviour.

Whatever the explanation for this phenomenon, it is clear that height models currently in use may need, under certain conditions, to be modified to account for the effect of stocking on height. No modification may be necessary if either or both of these criteria exist:

- The site is sheltered from wind;
- Early stocking has been very high (>2000 stems/ha).

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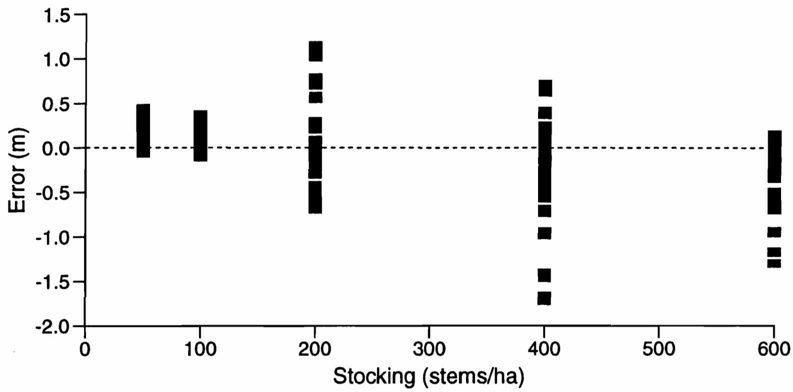
APPENDIX 1

TESTING THE BURKHART & TENNENT EQUATION AGAINST STOCKING



APPENDIX 2

TESTING THE BURKHART & TENNENT EQUATION AGAINST AGE