MONTHLY DIAMETER AND HEIGHT GROWTH OF YOUNG *EUCALYPTUS FASTIGATA, E. REGNANS,* AND *E. SALIGNA*

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ABSTRACT

Monthly tree heights and diameters were measured for sample stems of *Eucalyptus saligna* Smith over a period of 3 years, and of *E. regnans* F. Muell. and *E. fastigata* Deane & Maiden over a 5-year period. The *E. saligna* stand was located in a coastal Bay of Plenty forest; the other two species were in a central North Island forest. Diameter growth was fastest in October, with a secondary peak in March, and slowest in June, with a secondary trough in January. At its maximum, diameter growth was approximately double the minimum rate. The seasonal pattern in height growth was much more pronounced, peaking in December/January and at a minimum in June/July. There was little difference between the three species in seasonal patterns of diameter growth. Although the seasonal pattern in height growth appeared less pronounced for *E. saligna* than for the other two species, it is believed this may reflect site differences. The results confirmed that permanent sample plots should be measured during the winter months when growth is at its lowest. Monthly height and diameter percentage increments have been tabulated for use in eucalypt growth models.

Keywords: diameter; height; monthly growth; *Eucalyptus regnans*; *Eucalyptus fastigata*; *Eucalyptus saligna*.

INTRODUCTION

Eucalypt growing in New Zealand has had two significant peaks over the last 30 years. The first occurred during the late 1970s and early 1980s. According to Fry (1983) the New Zealand eucalypt resource in 1980 was 12 000 ha, of which 40% (4800 ha) had been established by Carter Holt Harvey Forests Ltd (CHH Forests). The annual planting rate by CHH Forests during this period was around 800 ha/annum (Poole & Fry 1980). By 1986 the CHH Forest resource was over 6300 ha, 64% of which were planted in *E. regnans* (Hayward 1987). The eucalypts (mainly *E. regnans* and *E. fastigata*) were grown as a replacement for indigenous sources of short-fibred hardwood pulp, and were to be used in mixture with *Pinus radiata* D. Don pulp. Subsequently, a strategic decision by CHH Forests in the late 1980s not to produce fine writing papers from short-fibre hardwood pulp (Edwards 1993) meant that no further plantings were undertaken. The New Zealand Forest Service (NZFS) in the early 1980s promoted the planting of eucalypts for sawn timber by developing regional planting targets (NZFS 1981). In addition to *E. regnans* and *E. fastigata* for planting in the cooler climates, *E. saligna* was the preferred species in the warmer, more northern parts of New Zealand. By 1996 over a thousand hectares of the latter species had been planted in plantations and farm woodlots (McKenzie & Hay 1996). However, current interest in *E. saligna* has declined due to persistent attack by a range of insect pests and slower growth rates than expected. Farm forestry enthusiasts around the country continued to establish small areas of a wide range of eucalypt species primarily for timber production.

The second planting peak began in the early 1990s and is continuing to increase. Two companies—Tasman Forest Industries Ltd (located in the Bay of Plenty) and South Wood Exports Ltd (based in Southland)—are planting eucalypts, mainly *E. nitens* (Deane et Maiden) Maiden, for short-fibred pulp or chip production. The current annual planting rate exceeds that of the early 1980s and has increased the New Zealand eucalypt resource.

A comprehensive silvicultural research programme on eucalypts is continuing at the New Zealand Forest Research Institute (Hay 1995; Kininmonth 1997). Part of this programme involves the regular measurement of over 500 Permanent Sample Plots (PSPs). Initially these plots were in stands and trials of *E. saligna* and *E. regnans*; however, latterly plots have been established in both *E. fastigata* and *E. nitens* stands. These measurement data have been used to develop growth models for *E. regnans* and *E. nitens* (Kininmonth 1997; Candy 1997). Traditionally these eucalypt PSPs have been measured in the winter when the growth of the trees was presumed to be slowest.

Although the growth of eucalypts in New Zealand can be particularly fast, especially in the initial stages after establishment, there has been no New Zealand information available on the effect of season on both height and diameter growth.

For 3 years, the diameters of 10 large *E. regnans* trees at Kinleith Forest (CHH Forests) were measured weekly (Poole 1986), starting at age 4 years. Using dendrometer bands, Poole found that the maximum diameter growth occurred in late spring (October–November) and the least growth in winter (June–July).

Similar growth periodicity for eucalypts was found by three other authors: Cremer (1975), using very young *E. regnans* seedlings in Tasmania, found that height growth over a 3-year period was nil or slight during September, the coldest month, but fastest during the warmest months of November through to February. The range of monthly diameter growth was less than that for height. Hopkins (1968) found that for 60-year-old Victorian regrowth of *E. regnans, E. obliqua* L'Her., and *E. radiata* Sieb. ex DC. diameter increased during most months, with a spring and early summer maximum, but ceased for about a month during winter. Incoll & Webb (1975), measuring 6-year-old *E. regnans* regrowth over a 3-year period, found that maximum height growth occurred 2 months after maximum girth growth. Girth growth, although variable, peaked in November and again in April and dropped markedly in winter. Eighty-one percent of height growth occurred between November and April, with a maximum peak in January and a secondary peak in April in 2 out of the 3 years.

By comparison, the height increment of *P. radiata* in New Zealand reaches maximum levels in October and November, and then again in March and April, and diameter increment reaches a maximum in February (Jackson *et al.* 1976). West *et al.* (1982) used Jackson's data to adjust *P. radiata* basal area and height increment data to an annual basis. A growth model predicting the effects of pruning and thinning of young *P. radiata* was developed from the adjusted data.

The eucalypt plantings established in New Zealand for sawn timber (NZFS 1981) meant that both pruning and thinning schedules had to be developed. The typical three-lift pruning schedules used for *P. radiata* (West *et al.* 1982) were initially proposed for the eucalypts; however, they were soon found to be inappropriate (Deadman & Calderon 1988). An understanding of the periodicity of eucalypt growth in New Zealand would be helpful in the development of future thinning and pruning schedules for eucalypts, as well as being integrated into the revision of the eucalypt growth models.

Tennent (1986) examined the monthly growth of *P. radiata* on four sites across New Zealand. There were differences in growth between the four regions with the northernmost site having almost continuous diameter growth and the southernmost site having a pronounced dormant period. On all sites, height growth began before diameter growth but slowed first at the end of the season. Diameter growth showed a marked fall-off towards the end of the growing season. A monthly growth adjustment for plots measured outside the "winter" months (April to July) has been included in the Permanent Sample Plot system (McEwen 1979).

Various methods have been used to model seasonal growth patterns in trees. Baker & Barker (1968) examined the seasonal growth pattern of three species. They used a second-degree polynomial to model the underlying growth trend and superimposed a sine curve to model the seasonal growth. Tennent (1986) modelled monthly growth increments using a polynomial equation of degree 7, conditioned to ensure a smooth transition between years.

The study reported here examined the seasonal growth pattern of young trees of three eucalypt species—*E. saligna, E. regnans*, and *E. fastigata*. Equations describing the seasonal growth pattern were derived and, from these, the percentages of diameter and height growth occurring in each month were tabulated. These can be used to provide seasonal adjustments to growth model predictions.

MATERIALS

Stand Histories

Three stands, one each of *E. regnans, E. fastigata*, and *E. saligna*, were chosen close to Rotorua, in the central North Island. All three sites, two in Kaingaroa Forest near Murupara, and one in Rotoehu Forest near Paengaroa, are regarded as individually suitable for the three eucalypt species. The first two species are better adapted to the cooler climate of the Murupara region, while the latter species is more suited to the warmer climate of Rotoehu Forest. The *E. regnans* diameter data of Poole (1986) were also analysed in this study. The climatic and establishment details of each trial site are shown in Table 1, along with a description of the Kinleith site used by Poole.

Tree Selection and Measurement

Existing on each of the Kaingaroa and Rotoehu Forest sites was a trial designed to compare the tree growth of different silvicultural treatments, superimposed over a range of initial spacings. For this study measurement trees of good form and vigour were randomly selected across a number of different tree spacings (Table 2). Heights and diameters of all selected trees were measured monthly. The heights were initially measured using graduated

TABLE 1–Climatic and establishment details of the four study sites.

Species	Forest*	Date planted	Altitude (m)	Rainfall (mm)	Soil classification	Previous site crop	Establishment techniques used
E. fastigata	Kaingaroa	1979	305	1323	Yellow-brown pumice	*Pinus ponderosa*	Site burnt. Pre-plant weed control. 60 g urea/tree
E. regnans	Kaingaroa	1978	210	1323	Yellow-brown pumice	*Pinus radiata*	Pre-plant/post-plant weed control. 60 g urea/tree
E. saligna	Rotoehu	1985	1550	1641	Kaharoa ash overlying Rotokawa ash	*Pinus taeda*	Post-plant weed control. 60 g urea/tree
E. regnans	Kinleith	1972	378	1550	Taupo sandy silt derived from Taupo ash	Pasture	400 kg urea/ha

* Prior to 1987 Rotoehu and Kaingaroa Forests were owned by the New Zealand Forest Service; currently owned by Fletcher Challenge Forests Ltd. Kinleith Forest is owned by Carter Holt Harvey Forests Ltd.

TABLE 2–Measurement details of the four species.

Species	Stockings sampled (stems/ha)	Number of trees measured	Start & finish dates (month/year)	Age (years)	Dbh Mean (cm)	Dbh MAI* (cm/yr)	Height Mean (m)	Height MAI (m/yr)
E. fastigata	Nelder†	20	October 1983	4.3	7.7	1.8	5.7	1.3
			August 1988	9.1	19.9	2.2	14.3	1.6
E. regnans	625, 1111, 2500, Nelder	40/35	October 1983	5.3	12.9	2.4	11.1	2.1
			October 1988	10.2	21.4	2.1	18.9	1.9
E. saligna	625, 1111, 2500	36	July 1987	2.0	4.5	2.2	4.3	2.1
			December 1990	4.9	10.7	2.2	9.2	1.9
E. regnans‡	350	10	October 1976	4.2	18.3	4.3	na	na
			October 1979	7.1	29.5	4.2	na	na

* MAI = mean annual increment

† A Nelder trial consists of trees planted in a series of concentric circles where the growing space available to each tree is determined by the distance to the nearest eight neighbouring trees (Nelder 1962)

‡ Data from Poole (1986)

na = not available

aluminium height poles. Pegs were placed beside each tree to provide a consistent reference point for the height pole. Once the trees became too tall (13 m), they were measured using a Suunto hypsometer and range finder. Breast height bands were marked on each tree, and diameters were measured with a standard plastic diameter tape. Measurements were made on approximately the same day in each month. Increments were annualised by dividing by the number of days in the interval, and multiplying by 365.

Within the *E. regnans* stand, 10 trees were selected in each of the four stocking levels available. The measurement of the 40 trees commenced in October 1983 and ceased in August 1988. During normal silvicultural operations in November 1986, five trees were removed thereby reducing the measurement sample to 35. One of the 59 monthly measurements was not collected.

Twenty *E. fastigata* trees were selected in the Nelder (1962) trial. Measurements began in October 1983 and ceased in August 1988. One of the 59 monthly measurements was not collected.

Thirty-six *E. saligna* trees were randomly selected for measurement through the three different spacings of the regime trial. Measurement commenced in July 1987 and continued through to December 1989. One of the 30 monthly measurements was not collected.

Data Analysis

For each measurement, mean heights and diameters were obtained for each stand. These were then used to obtain height and diameter growth rates, calculated by dividing the growth increment by the length of the measurement period in days. To allow data from different species and sites to be compared, growth rates within each stand were standardised by dividing them by their average. This standardised growth rate was used as the dependent variable in a regression containing the following terms:

$$\text{standardised growth rate} = f(\text{species, age}) + g(p)$$

The first term on the right-hand side of this equation allowed for long-term trends in growth rate for each species. These were adequately accounted for by using a linear term in age with separate slopes and intercepts for each species.

The seasonal growth pattern was modelled by the function g(p) where p is the elapsed proportion of year at the midpoint of the measurement increment period (i.e., p = 0 on 1 January, and p = 1 on 31 December). A method similar to that of Tennent (1986) was used, with g(p) being a polynomial in p constrained to achieve a smooth transition between years. The smooth transition was achieved by ensuring that the function and its first and second derivatives were equivalent at the beginning and end of the year and took the following form:

$$g(p) = b_1 z_1(p) + b_2 z_2(p) + b_3 z_3(p) + \ldots$$

As shown in the Appendix, the functions $z_i(p)$ which satisfy the constraints are of the form:

$$z_i(p) = {}^1\!/_{12}\, i\,(i-1)p + {}^1\!/_4\, i\,(i+3)p^2 - {}^1\!/_6\,(i+3)(i+2)p^3 + p^{i+3}$$

The regression was fitted using standard linear regression software, although the associated tests of significance were treated with caution owing to likely autocorrelation among the error terms. The procedure adopted was to successively add $z_1(p)$, $z_2(p)$, $z_3(p)$, etc., until no further significant improvement in fit was obtained. A single regression combining all species was fitted, but tests for species differences in the seasonal growth coefficients were also obtained.

Because the long-term trend effects were species- and site-specific, they are replaced in the general form of the equation by a single intercept which was chosen such that the integral of the growth rate over 1 year was one. Thus, the general form of the equation was

$$\text{standardised growth rate} = a + g(p)$$

where,

$$a = 1 - \int_0^1 g(p)dp$$

The percentage of annual growth occurring in each month was obtained by integrating this function over the month.

RESULTS

Mean standardised monthly growth rates (Table 3, Fig. 1 and 2) showed similar patterns for all species. Diameter growth was fastest in spring and slowest in winter, but always greater than zero. The reduced winter growth rate was probably a result of the cooler temperature (Table 4) and other factors such as reduced solar radiation. There was also a slight growth reduction in summer and an increase in autumn, possibly caused by the reduced summer rainfall (Table 4). Height growth peaked in spring and was greatly reduced in winter. Mean heights even decreased in some months for *E. regnans* and *E. fastigata*. Although the cause of this reduction in height growth is uncertain, it may well have been due to the periodic effects of insect or fungal attack, primarily *Mycosphaerella* spp. during the winter and early spring. Additionally, climatic factors such as wind or rain may cause damage and subsequent tip die back. Such damage may occur at other times during the growing season but be masked by a greater growth increment.

TABLE 3–Mean monthly growth rates for dbh and height. Growth rates have been standardised by dividing by the average annual growth rate.

Month	Standardised monthly dbh growth rates				Standardised monthly height growth rates		
	E. fastigata	*E. regnans*	*E. saligna*	*E. regnans**	*E. fastigata*	*E. regnans*	*E. saligna*
Jan	0.92	0.83	0.92	1.18	3.44	2.96	1.54
Feb	1.46	0.85	1.24	1.27	2.48	3.70	1.38
Mar	1.21	1.13	0.98	1.28	2.02	1.11	1.33
Apr	1.15	1.04	1.24	0.69	1.51	1.36	0.86
May	1.01	1.09	1.61	0.48	0.41	0.15	0.99
Jun	0.56	0.67	0.33	0.41	–0.06	0.68	0.12
Jul	0.14	0.28	0.42	0.70	–0.73	–2.37	0.60
Aug	0.34	0.67	0.98	0.85	0.62	1.46	0.37
Sep	1.57	1.89	1.16	1.32	–0.91	–1.72	0.88
Oct	1.56	1.67	1.19	1.54	–0.47	0.98	1.69
Nov	1.11	1.02	1.01	1.21	1.84	1.74	1.36
Dec	0.97	0.87	0.93	1.08	1.85	1.96	0.87

* Data from Poole (1986)

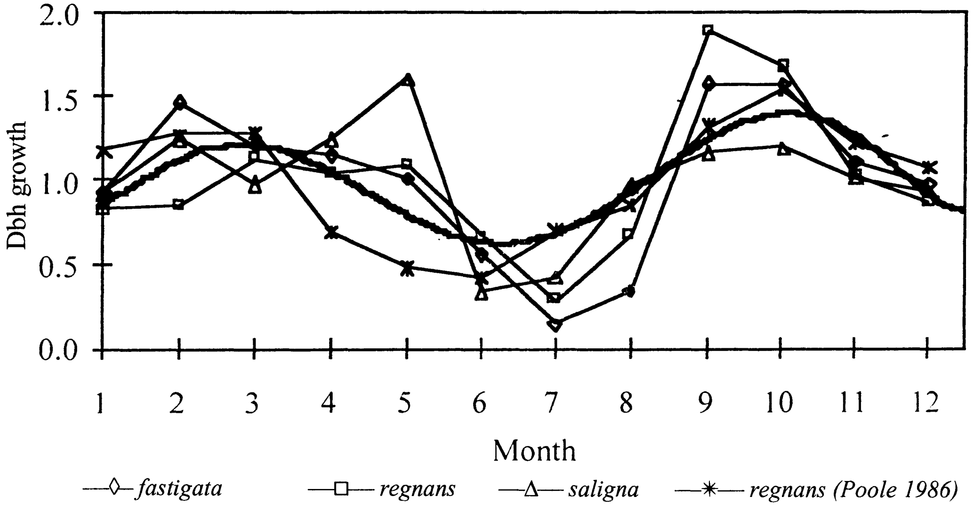

FIG. 1–Dbh growth rate data and fitted equation. Growth rates have been standardised by dividing by the average annual growth rate.

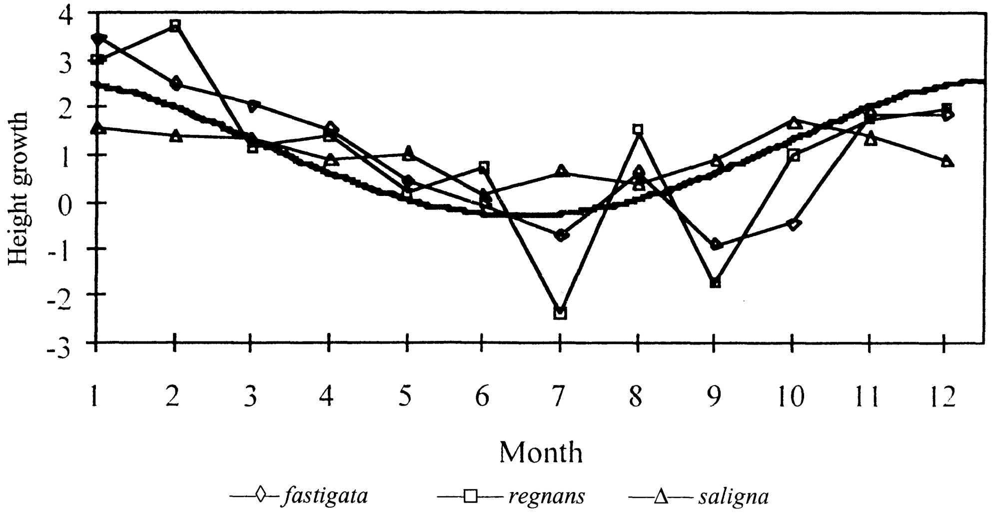

FIG. 2–Height growth rate data and fitted equation. Growth rates have been standardised by dividing by the average annual growth rate.

The regression analysis indicated that at least three terms were required to model dbh seasonal growth adequately. The third term was highly significant ($p<0.0001$). Although the fifth term was also statistically significant, the three-term model was adopted as it combined simplicity with an adequate fit. There were no significant differences between species in the seasonal growth, and so a single equation was used for all species (Table 5, Fig. 1).

TABLE 4–Mean, minimum and maximum daily temperatures and mean monthly rainfall at the three sites, 1932–80 (New Zealand Meteorological Service 1983)

Month	Temperature (°C)									Mean monthly rainfall (mm)		
	Murupara			Kinleith			Rotoehu			Murupara	Kinleith	Rotoehu
	Mean	Min.	Max.	Mean	Min.	Max.	Mean	Min.	Max.			
Jan	18.5	12.0	24.9	17.3	11.9	22.7	17.8	12.1	23.4	103	96	99
Feb	18.7	12.5	24.9	17.4	12.0	22.8	18.0	12.6	23.5	126	96	122
Mar	16.8	10.7	22.7	16.0	11.1	21.1	16.5	11.0	22.1	91	95	135
Apr	13.5	7.6	19.3	13.0	8.4	17.6	13.8	8.1	19.4	101	110	132
May	9.4	3.4	15.4	9.7	5.4	13.9	10.9	5.3	16.4	123	143	163
Jun	7.3	1.8	12.7	7.5	3.6	11.4	8.5	3.0	14.0	120	151	154
Jul	6.8	1.1	12.4	6.9	2.8	10.9	7.9	2.3	13.4	118	145	163
Aug	8.3	2.6	13.8	8.2	4.1	12.2	8.9	3.4	14.3	116	164	173
Sep	10.0	4.4	15.6	9.7	5.4	13.9	10.5	4.8	16.1	103	165	129
Oct	12.5	6.6	18.3	11.6	7.0	16.1	12.4	7.0	17.9	102	140	134
Nov	14.5	8.3	20.6	13.8	8.8	18.7	14.4	8.8	19.9	98	146	106
Dec	16.8	10.5	22.9	15.7	10.7	20.7	16.3	10.8	21.7	122	149	131
Mean	12.8	6.8	18.6	12.2	7.6	16.8	13.0	7.7	18.5	1323	1600	1641

TABLE 5–Coefficients (with standard errors) of height and dbh equations.

	Dbh	Height
intercept	0.81	2.51
b_1	785.2 (157.7)	–45.4 (5.5)
b_2	–732.6 (145.3)	
b_3	245.5 (48.4)	

Only the first term in the seasonal regression model for height growth was significant ($p<0.0001$). The seasonal response differed significantly between species ($p=0.014$). This reflected the fact that the *E. saligna* showed a less marked seasonal variation in height growth than the other two species (Table 3, Fig. 2). It was more likely a result of the milder winter climate at the Rotoehu site than a genuine species difference. A single equation was therefore adopted for all species (Table 5, Fig. 2).

Predicted monthly increment as a percentage of annual increment in diameter and height was derived from the regressions and is presented in Table 6. Diameter increment was greatest in October with a secondary peak in March, and was smallest in June with a secondary trough in January. At its maximum, diameter increment was approximately double the minimum rate. The seasonal pattern in height growth was much more pronounced, peaking in December/January with 40% of total annual growth occurring in these 2 months. Height growth was at a minimum in June/July. From these growth patterns, it appears that height growth is controlled primarily by temperature, while diameter growth is affected by both temperature and rainfall.

TABLE 6–Percentage of annual dbh and height increments occurring in each month.

Month	Dbh increment (%)	Height increment (%)
Jan	7.2	20.1
Feb	9.2	16.3
Mar	9.9	10.8
Apr	8.7	5.0
May	6.7	0.2
Jun	5.3	–2.3
Jul	5.7	–2.3
Aug	7.7	0.2
Sep	10.2	4.8
Oct	11.4	10.6
Nov	10.4	16.3
Dec	7.7	20.1

In growing a eucalypt crop, especially for sawlogs, a series of thinning operations will be required. One way of increasing the crop yield is to apply additional fertiliser at time of thinning. In a thinning and fertiliser study with 7-year-old *E. regnans*, Messina (1992) found that a combination of fertiliser and thinning (nitrogen fertiliser at 500 kg/ha and thinning from 1200 to 350 stems/ha) gave the largest response in diameter growth of crop trees. Knight & Nicholas (1996) reported on a similar study (Kaingaroa Forest) where crop-tree productivity gains resulted from a combined response to thinning and fertiliser application (nitrogen (250 or 500 kg/ha) and thinning from 1667 to 600 stems/ha). The current study suggests that, to maximise its effect, fertiliser should be applied in early spring to coincide with the seasonal peak in diameter growth (Table 6).

CONCLUSIONS

A clear pattern of variation in monthly growth rate of dbh and height for all three species was observed between summer and winter. The three species, *E. regnans, E. fastigata*, and *E. saligna* appeared to follow a similar pattern, with height growth peaking in December/January and lowest in June/July, and diameter growth peaking in October and lowest in June. There was also a secondary peak in diameter growth in March. Differences between species and sites were not detectable in this study because the effects of species and site were confounded.

This study:

(a) Confirmed that PSP measurements of the ash group eucalypts (including *E. regnans* and *E. fastigata*) and *E. saligna* should be undertaken in June or July when height growth is at a minimum;

(b) Provided a prediction of monthly height and diameter growth adjustment which can be used in the development and application of growth models;

(c) Indicated the pattern of seasonal variation in both diameter and height growth for *E. regnans, E. saligna*, and *E. fastigata*, providing information on timing of thinning and fertiliser application to best capture maximum growth.

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