INTRA-ANNUAL GROWTH OF YOUNG PINUS RADIATA IN NEW ZEALAND

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ABSTRACT

Height and diameter growth of 5-year-old **Pinus radiata** D. Don was measured monthly at four forests throughout New Zealand. A conditioned seven degree polynomial was fitted to the cumulative growth. The differential was used to calculate the proportion of growth in each month. There were significant differences in growth pattern between the four forests.

Keywords: increment; growth patterns; polynomial; **Pinus radiata**

INTRODUCTION

Forest management in New Zealand has progressed from using 5-year age-classes, through the use of annual increments, to using the growth of a stand throughout the year. Managers are now interested in monthly growth patterns.

In the past, management has planned for silvicultural operations to be carried out at a certain stand age or height. However, this is no longer accurate enough. Growth models provide estimates of annual growth, and such estimates have a variety of end uses. Shirley & Coker (1986) discussed scheduling silviculture and emphasised the importance of determining the month a stand reaches a predefined threshold value of predominant mean height. The procedure they described uses the Stand Record System (Shirley 1983) to provide a stand's recent statistics. These statistics are updated using growth models which provide annual estimates of growth, but a method is then needed to distribute the predicted annual growth within the year.

Growth modellers also need to be able to distribute growth within years to enable the use of data from increment periods which are not exactly year-long intervals (Garcia 1979).

The standard method of distributing growth within a year (e.g., West *et al.* 1982) has been to apply the adjustments derived by R. W. Jackson (pers. comm.) who examined the growth of *P. radiata* over a 4-year period. Previous work by J. Beekhuis (unpubl. private papers) had provided similar estimates.

Jackson *et al.* (1976) studied the effects of drought on *P. radiata* growth, and made comparisons with data from R. W. Jackson (pers. comm.) and other unpublished sources. The trees studied were grown in lysimeter boxes and, although the study is indicative, the results could not be described as representative of forest conditions. Their study demonstrated that drought could affect the growth pattern.

The study reported here examined the growth of young *P. radiata* within the year on sites throughout New Zealand with the aim of providing a means of distributing growth within years.

METHODS

The four forests chosen for this study represented a wide range of conditions (Table 1). Aupouri State Forest is New Zealand's northernmost forest, which provided one extreme. Whakarewarewa State Forest Park, adjacent to the Forest Research Institute at Rotorua, has a climate representative of the central North Island forest plantations. A trial had been established at Mohaka State Forest, on the East Coast of the North Island. Otago Coast State Forest provided a southern extreme typical of the low altitude forests of the Southland region.

TABLE 1—Description of forests studied

Forest	Latitude	Longitude	Elevation (m)*	Mean annual precipitation (mm)*	Mean annual temperature (°C)*
Aupouri	173° E	35° S	69	1187	16.0
Whakarewarewa	176° E	38° S	307	1439	12.6
Mohaka	177° E	39° S	286	1659	12.8
Otago Coast	170° E	46° S	15	773	10.1

* At the nearest weather station – long-term trends from N.Z. Meteorological Service (1983).

A trial was established at Aupouri to study the growth of 5-year-old *P. radiata* under a variety of thinning, pruning, and fertiliser treatments (T. Baker, pers. comm.). Two trees were selected randomly in each of the 36 trial plots of 0.04 ha. Each tree was paint-banded at the centre of the internode nearest to 1.4 m, and a peg was hammered into the ground at the base of each tree as a reference point. The diameter over the band was measured to the nearest millimetre, and the height was measured by placing a calibrated height pole on the peg and reading the decimetre height class in which the tallest shoot extension lay. The diameter and height of each tree was measured at the start of each month from September 1983 until June 1985, with the exception of October 1984 when a measurement was missed. After each measurement, diameters and height were checked against the previous month's data, and remeasured when errors were suspected. For the present analysis only the data from the two trees in each of the 18 plots without fertiliser were used.

Four 0.01-ha plots were established in Whakarewarewa, one in April 1983 and three in November 1983. The plots were established in 5-year-old stands which had been thinned to 600 stems/ha and low pruned. Diameter and height measurements were collected using techniques similar to those at Aupouri. The plots were measured monthly until July 1985.

Four 0.01-ha plots were established in January 1984 at Otago Coast State Forest in 5-year-old low-pruned stands which had been thinned to 1000 stems/ha. The plots were measured monthly, using the techniques described above, until July 1985.

A trial had been established at Mohaka State Forest in July 1982 and data from this (N.Z. Forest Service, unpubl. data) were included in the analysis. Four plots had been established and had been measured each month until May 1985. The trial had been low-pruned and thinned to 850 stems/ha.

The resultant data set is thus derived from different stands, and has been collected over three growth periods (Table 2).

TABLE 2—Source of the measurements used in the analysis

Forest	Number of plots	Selected measurement period	Number of monthly plot measurements
Aupouri	18	May '84 - May '85	11*
Whakarewarewa	4	May '83 - May '85	60
Mohaka	4	May '83 - May '85	96
Otago Coast	4	May '84 - May '85	48

* All plots combined.

ANALYSIS

The data were analysed by examining the mean monthly dbh and height for each forest. The heights and diameters of all trees which were alive at the end of the measurement period were summed by months for all plots. These statistics were based on the 36 trees for the Aupouri trial and all surviving trees for the other forest sites. (Two trees died during the measurement period.)

The Aupouri data set is of a slightly different nature to those from the other sites in that it is from 36 trees within 18 plots, whereas the other data sets include all trees in four plots, with the exception of the 1983 Whakarewarewa data. The Aupouri statistics may represent these differences, and may therefore be considered inconsistent with those of the other sites. The data were included in the analysis because of the importance of the forest's location at the far north of New Zealand. All plots with fertiliser were excluded from the Aupouri data set.

The statistics were combined to form a data set composed of six series of diameter and height statistics. There were a variety of starting and finishing measurement months, with October 1984 missed in the Aupouri data.

The analysis was to be carried out using a set starting month for all sites. The over-all lowest monthly growth for the entire data set occurred in May and so this was chosen as the starting month, and the analysis was carried out on a May-to-May year. The cumulative percentage growth by month was calculated from the summed statistics.

The data of Beekhuis (unpubl.) and the studies of R. W. Jackson (pers. comm.) and Jackson *et al.* (1976) have given rise to the hypothesis that there are two growth "bursts" within each annual growth period. Intra-annual growth has been considered to have a bi-modal distribution and so a function chosen to represent such growth must be capable of displaying such a pattern. In this study it was decided to fit a polynomial to the cumulative distribution of growth, and to use the differentiated form of the model to examine the monthly growth pattern. The polynomial was conditioned to have a zero intercept, have a value of 100 after a full year's growth, and to be continuous at the start and end of each year to ensure that subsequent years show similar patterns. To allow a bi-modal monthly pattern to be represented by the differential, a polynomial of degree 7 is required.

This produced the following model

$$y = a_1x + a_2x^2 + a_3x^3 + a_4x^4 + a_5x^5 + a_6x^6 + a_7x^7$$

subject to:

$$a_1 + a_2 + a_3 + a_4 + a_5 + a_6 + a_7 = 100$$
$$2a_2 + 3a_3 + 4a_4 + 5a_5 + 6a_6 + 7a_7 = 0$$
$$6a_3 + 12a_4 + 20a_5 + 30a_6 + 42a_7 = 0$$

where $0 <= x <= 1$, the proportion of the year

$0 <= y <= 100$, the cumulative growth percentage

and a_i are coefficients.

The model was fitted to the height and diameter increment data for each region and for the combined data set. The estimated monthly increment percentage was calculated from the differential of the model. All models were significant at $p < 0.001$, as tested against a line through (0,0) and (1,100) by the conditional error test (*see* Draper & Smith 1966, p. 74).

Diameter bimodality was investigated further by fitting the model as a polynomial of degree 9. It was also investigated by fitting the model separately for each year in the two data sets where there were 2 years' data for plots.

Extending the model to degree 9 did not show any further evidence of bimodality. The fitting to successive years produced functions which were very similar. For Mohaka State Forest the two functions differed at the 5% level for diameter growth, but were not significantly different for height growth. For the one plot at Whakarewarewa State Forest with two series of annual measurements the functions differed at the 1% level for diameter and at the 5% level for height. In view of the general similarity between the functions and the low level of significance of the differences, the successive years were averaged, weighted by plots, to give one set of annual data for each region. The analysis was repeated for this final data set.

RESULTS

The monthly diameter and height increments and the predicted values for the four regions and for the over-all data set, as the percentage of annual increment in each month, are summarised in Fig. 1–6. The percentage of annual increment predicted from

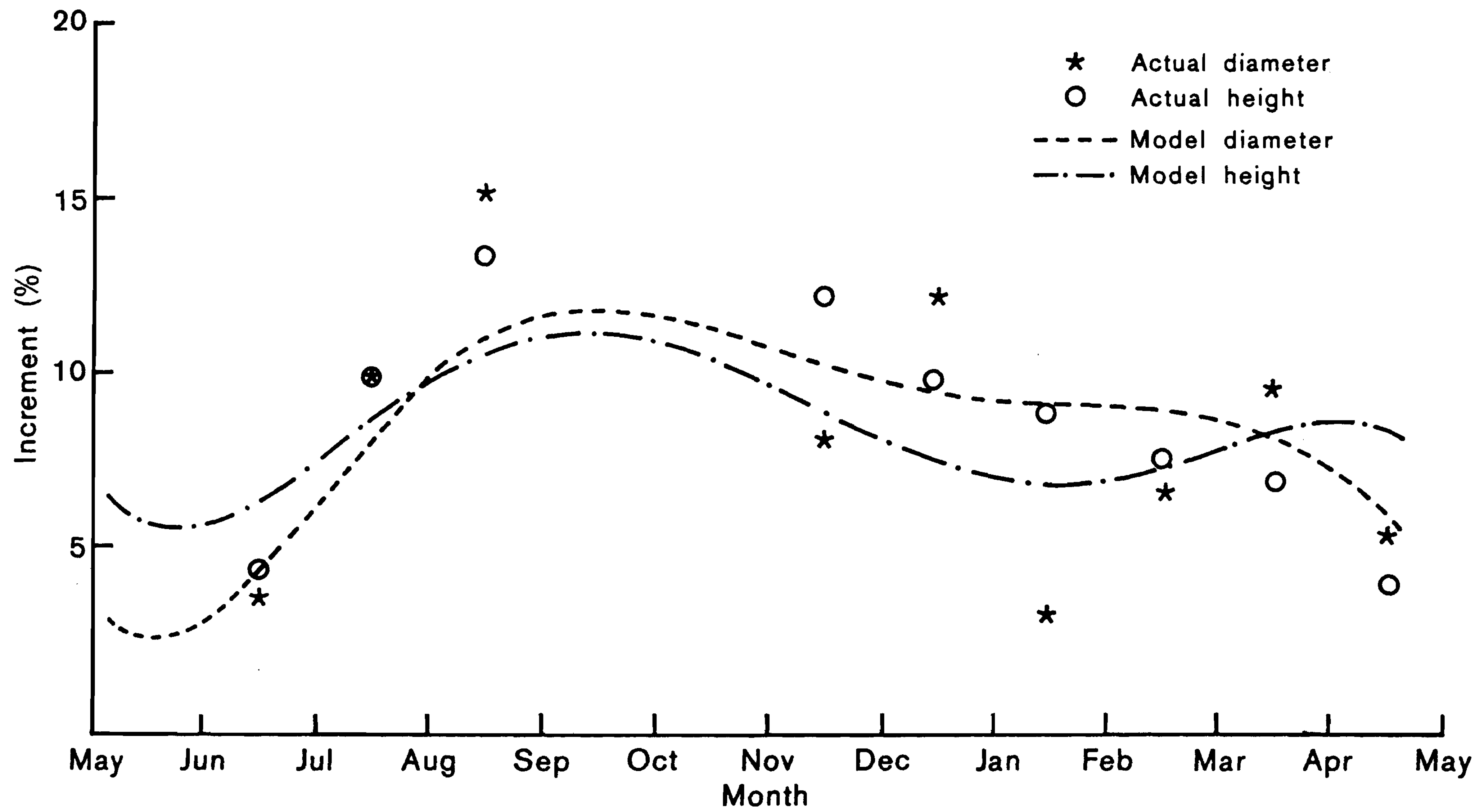

FIG. 1—Monthly percentage diameter and height increment in Aupouri Forest.

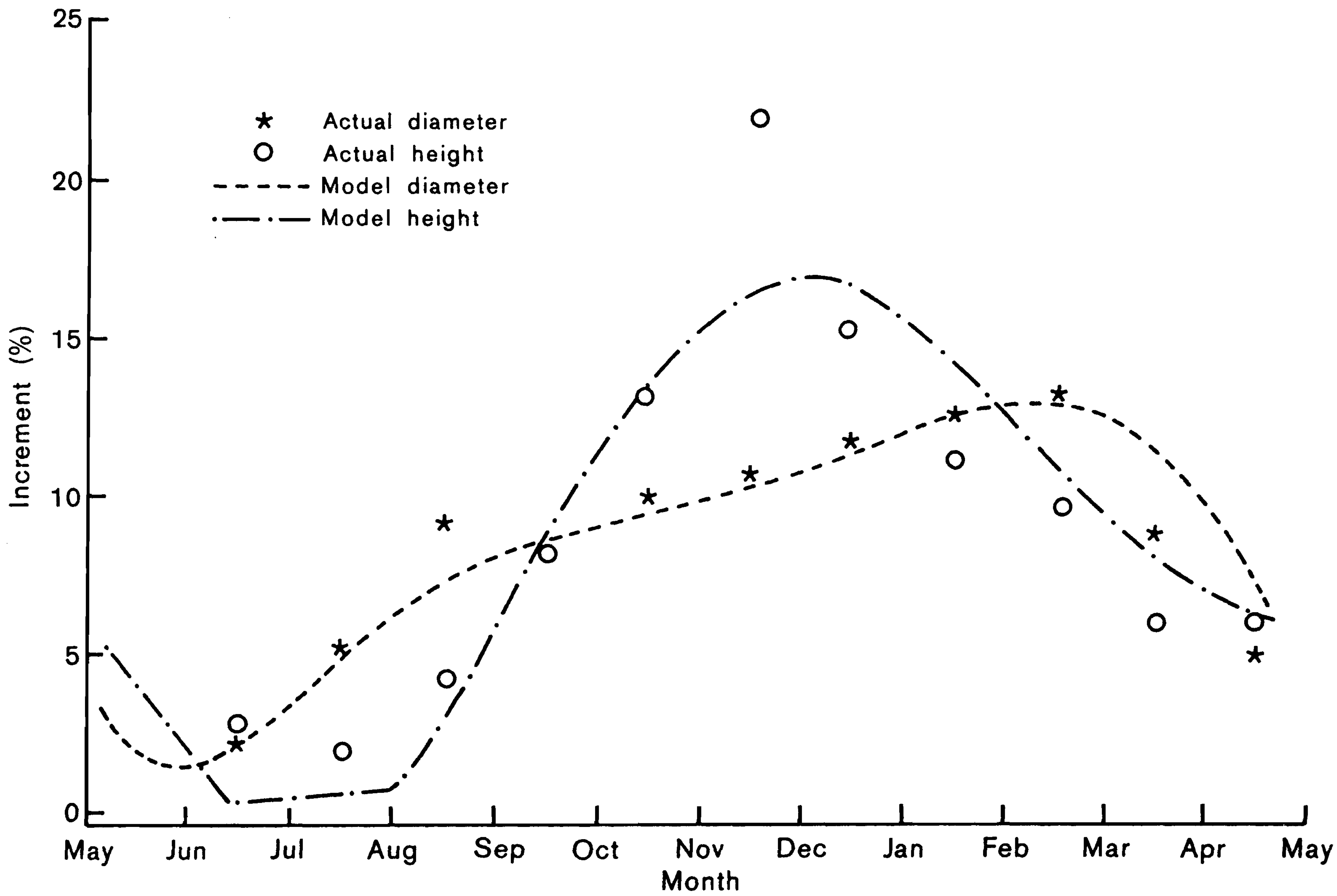

FIG. 2—Monthly percentage diameter and height increment in Whakarewarewa Forest.

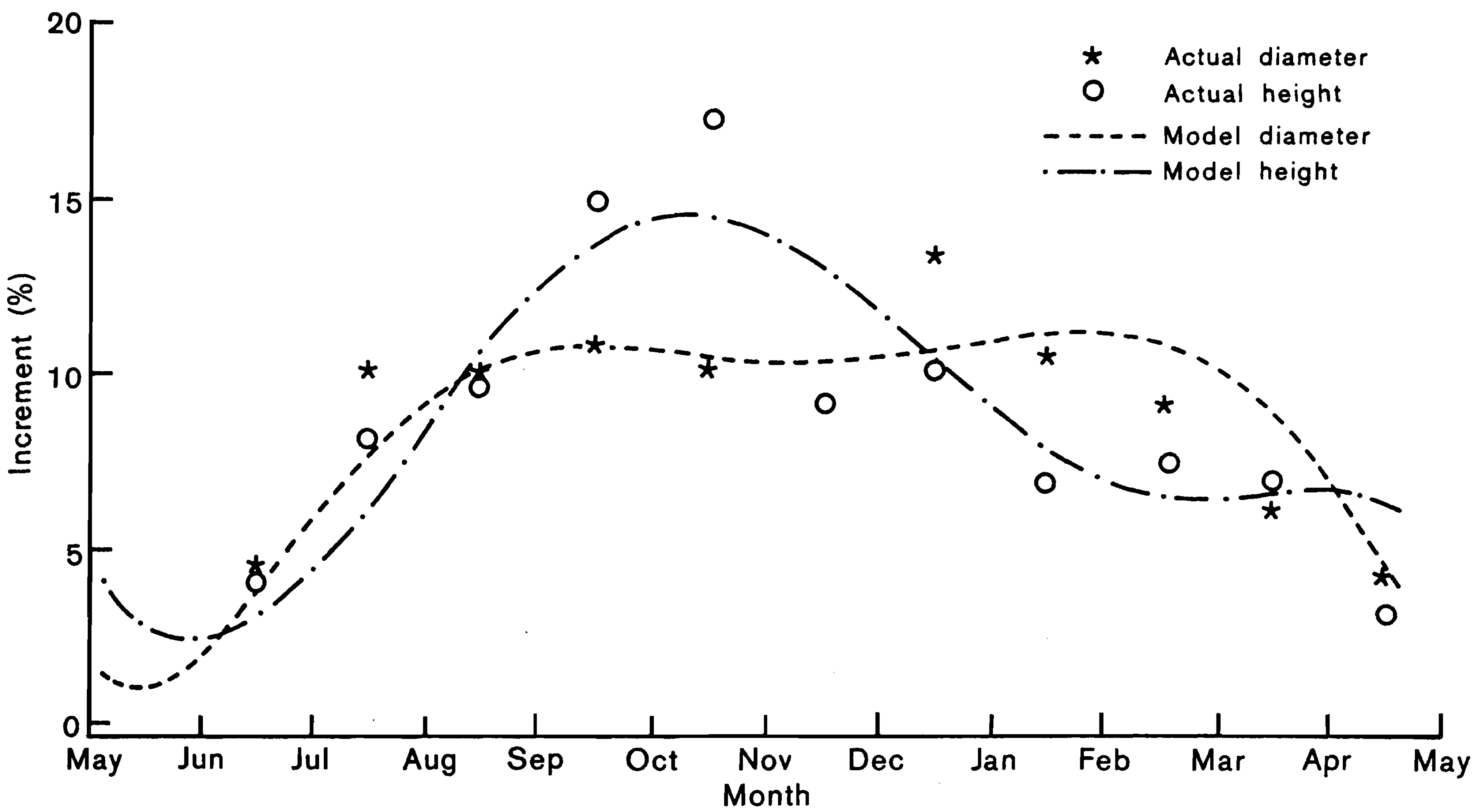

FIG. 3—Monthly percentage diameter and height increment in Mohaka Forest.

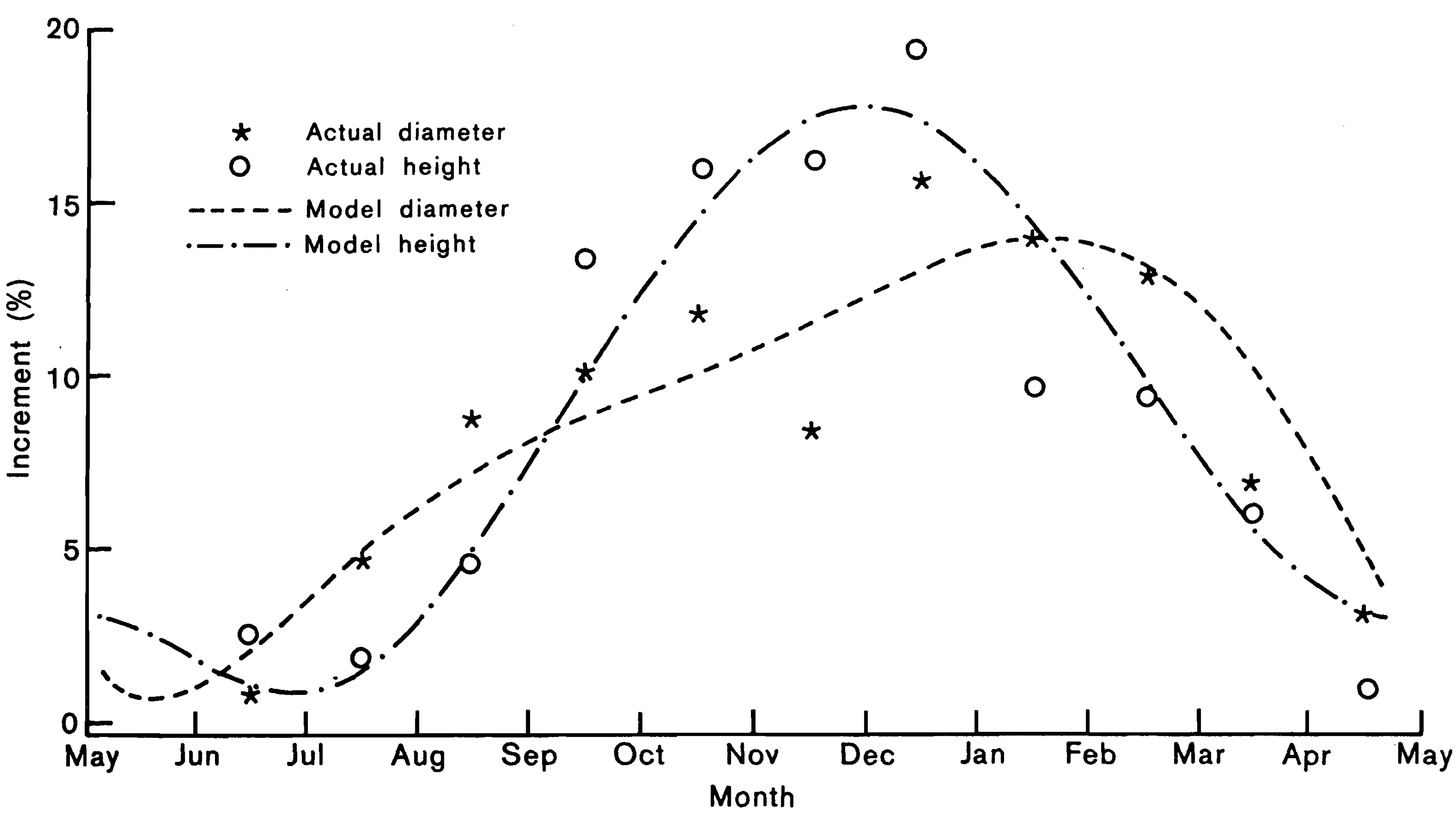

FIG. 4—Monthly percentage diameter and height increment in Otago Coast Forest.

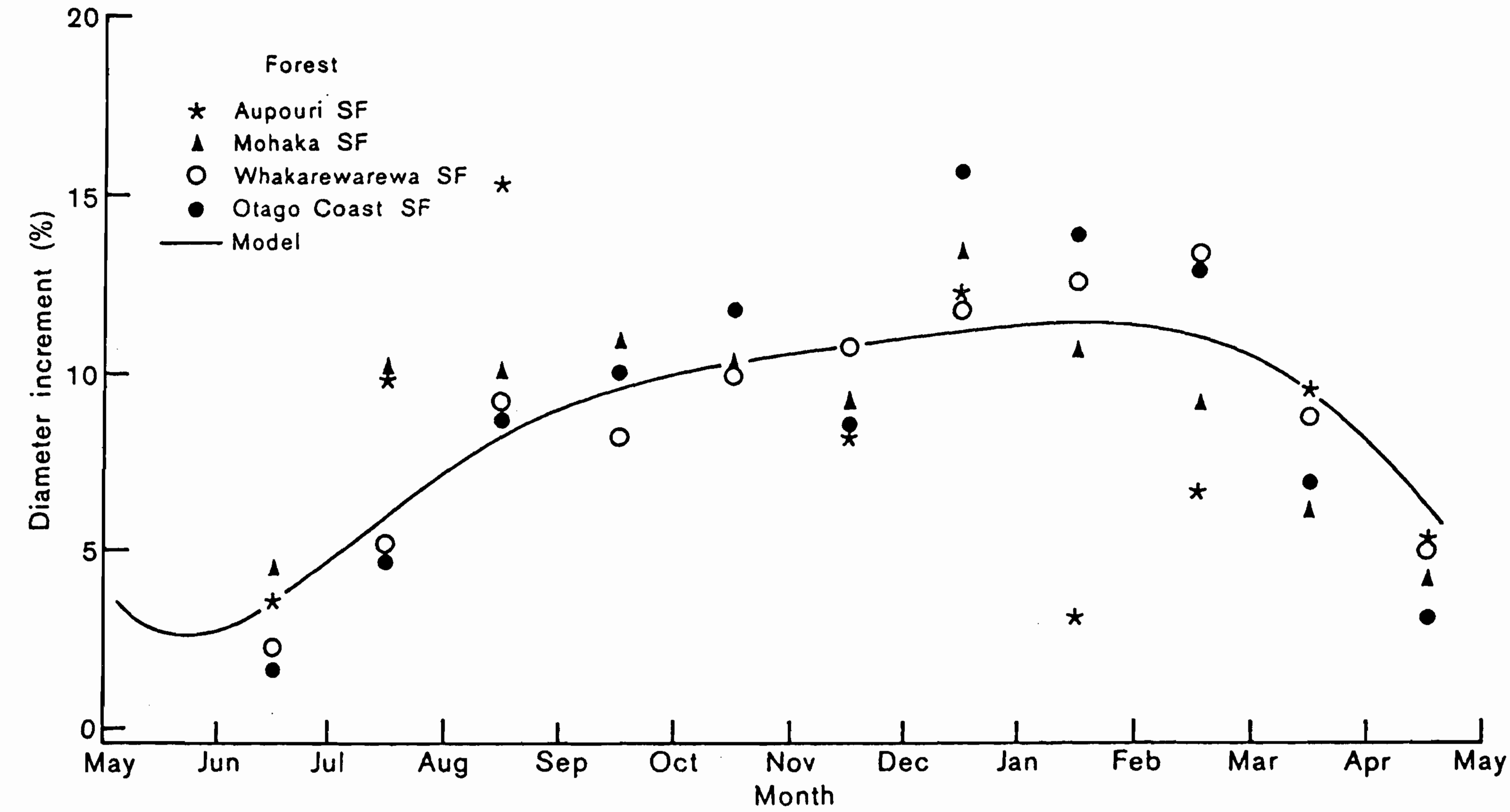

FIG. 5—Monthly percentage diameter increment for the combined data set.

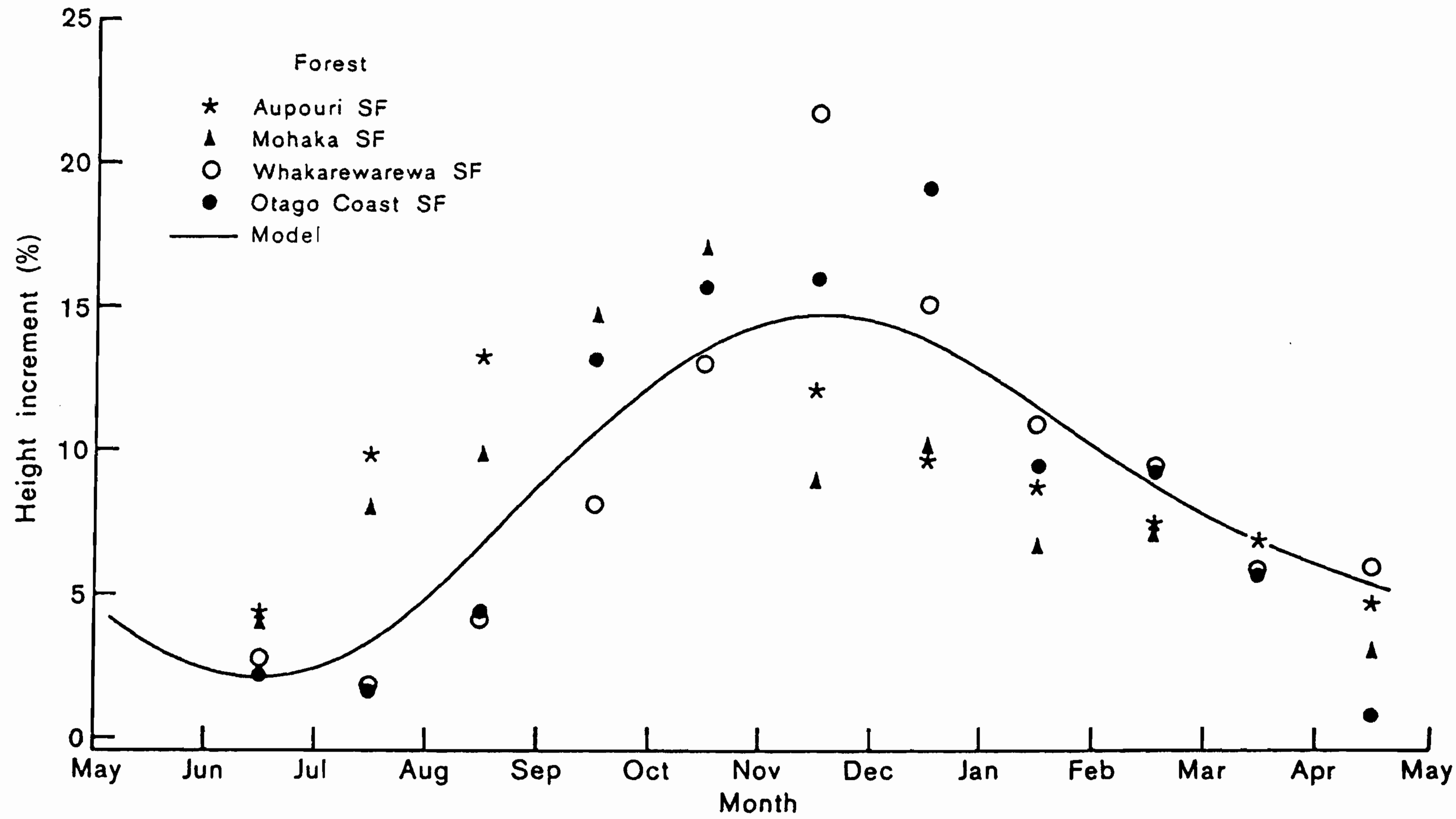

FIG. 6—Monthly percentage height increment for the combined data set.

the model for diameter and height in each region, and using the combined data set, is given in Table 3. The data fit the model; there is little indication of a bimodal distribution for height increment, and only a slight indication of bimodality in diameter increment.

TABLE 3—Predicted monthly diameter and height increment as a percentage of total annual increment

Forest	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
					Diameter increment (%)							
Aupouri	6.9	7.6	8.5	7.1	5.6	7.1	9.2	11.0	11.1	10.1	8.3	7.2
Whakarewarewa	12.8	12.7	10.6	4.4	1.4	3.0	5.5	7.9	8.9	9.6	10.7	11.7
Mohaka	11.2	10.3	7.7	2.2	1.6	5.1	8.5	10.5	10.7	10.4	10.4	10.8
Otago Coast	13.9	12.3	8.6	2.2	0.8	3.0	5.6	7.9	9.2	10.4	12.1	13.4
Combined	11.3	10.6	8.6	4.3	2.6	4.3	6.6	8.8	9.8	10.4	10.9	11.2
					Height increment (%)							
Aupouri	9.0	8.7	7.6	3.7	2.5	5.5	8.9	11.4	11.8	11.1	10.0	9.3
Whakarewarewa	12.7	9.5	7.2	5.4	2.1	0.0	0.2	4.9	10.0	14.3	16.8	16.0
Mohaka	6.8	6.2	6.5	4.7	2.2	3.8	7.3	11.9	14.0	14.2	12.1	9.4
Otago Coast	12.3	7.9	4.4	3.0	1.9	0.7	1.8	6.4	11.2	15.2	17.5	16.5
Combined	10.3	8.0	6.3	4.5	2.4	2.2	4.0	8.2	11.6	13.9	14.5	13.2

Comparisons between Fig. 1 to 4 suggest that there are different patterns between regions. The wide scatter of data around the curves in Fig. 5 and 6 support this. Three null hypotheses were examined.

The first null hypothesis was that there was no difference in growth between the regions. This was examined by testing the significance between the four forest models and the over-all model, using the conditional error test (Draper & Smith 1966). This null hypothesis was rejected for both diameter and height growth, with $F_{12,31}$ of 45.3 and 60.2 respectively.

The second null hypothesis was that there were two regions – Aupouri, and the other three forests. This null hypothesis was also rejected for both diameter and height growth, with $F_{8,31}$ of 20.2 and 67.6 respectively.

The final null hypothesis was that there were three regions – Aupouri, Mohaka, and the remaining two forests. This null hypothesis was also rejected with $F_{4,31}$ of 3.9 for diameter growth and 13.5 for height growth.

The restrictions imposed on the model were not statistically significant. This indicates that the restrictions, imposed to force the model to fit the preconceived hypothesis that growth is continuous from year to year and to condition the model to rise from 0% to 100% within 1 year, are suitable.

To validate the models would require an independent data set in each region, but this was not available. However, the Whakarewarewa plots had been measured from November 1983 until the start of the study period. May 1984, and the Mohaka plots had data from July 1982 until May 1983. These data were used to examine the two relevant models.

Estimates of the annual diameter and height increments were made assuming the models were exactly correct for the November 1983 and July 1982 measurements. The differences in predicted growth and actual growth were calculated. This gave 14 observations for diameter and height increment.

For the 14 diameter observations all observed increments were within ± 10% of their predictions, and 10 were within ± 5% of their predictions. For the 14 height observations 12 were within ± 10% and eight were within ± 5%.

This validation is highly dependent on the estimate of the annual increment, which depends on the nature of the first observation. It is not conclusive, but does indicate a general agreement between the models and a set of observations not used in the model development.

DISCUSSION

The patterns shown in Fig. 1 to 4 demonstrate that there are differences in growth between the different regions studied. There is a limited amount of data for Aupouri, and the data were collected in a different manner from the rest of the data set. However, there is a strong indication that diameter growth is almost continuous throughout the year. In contrast, Otago Coast shows a pronounced dormant period in winter. The three null hypotheses examined indicate that growth varies throughout New Zealand.

The comparison between height and diameter growth supports the hypothesis that height growth leads diameter growth in *P. radiata*. In all forests the height growth build-up begins before the diameter increase. Height begins to slow before diameter, with diameter growth showing a sharp fall-off towards the end of the growing season.

The hypothesis that growth has a bimodal pattern is not supported. The indications are that growth may be bimodal in any one year, but that this may be more an effect of any one growing season's weather than an intrinsic pattern. An alternative hypothesis is that the data and method of analysis disguise any such pattern, as peaks in successive years may be merged by the regression analysis (Kozlowski & Ward 1961). As only 2 successive years' data were available there are too few data for a conclusive statement. This issue can be resolved only by a more extensive series of measurements, extending over at least 4 years.

There is little evidence of a common New Zealand growth pattern. Growth patterns are likely to vary widely throughout the country.

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