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Relationship of Daily Growth and Development of Peach Leaves and Fruit to Environmental Factors

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Abstract. **A procedure was developed for detecting daily changes in the rate of growth and development of leaves and fruit of peach [*Prunus persica* (L.) Batsch.]. Quantitative morphological stages of leaf and fruit development were determined for 3 cultivars, transformed into growth rates, and used as dependent variables for regression on a variety of daily environmental variables: maximum and minimum temperature, degree hours, precipitation, solar radiation, estimated soil moisture (Thornthwaite method), 1- to 3-day lags of these variables, quadratic and cubic transformations, and selected 2-variable products of the basic variables. Prediction equations performed well in tests from different years, locations, and cultivars. Maximum and minimum temperature, precipitation, soil moisture, and age were the most important variables for the leaf growth prediction equation. In the fruit growth prediction equation, maximum and minimum temperature, soil moisture, and age were most important.**

Peach yields vary greatly from year to year. Although a large part of yield variation is due to weather, precise growth and developmental responses have not been identified. We describe a method for detection of daily quantitative morphological changes in leaves and fruit of peach and relate these changes to environmental factors.

Daily morphological changes in leaves have been quantified for several species of annual plants (6, 7, 8, 9, 10). These include size and number of leaves and their stage of development. The daily status of plant development is determined by the average number of leaves on an appropriate number of labeled plants each day; the daily growth rate is obtained by the change in status from the previous day. Since the same growing points are involved in successive observations, and destructive harvests are unnecessary, the statistical problems of sampling and plant measurement are greatly minimized.

Materials and Methods

Plant material. Growth prediction models developed from daily measurements of 'Redhaven', 'Redglobe', and 'Rio-Oso-Gem' (all on Lovell seedling rootstocks) at Clemson, S.C. on Cecil sandy loam in 1981 were tested on independent sets of measurements of 'Redskin' near Pendleton, S.C. on a Cecil clay loam, made 3 times per week in 1966 and 5 times per week in 1971. Trees were spaced 6 × 6 m with a 3-m herbicide strip centered on each row. Observations were started at each site when the trees were in their 5th year, about 2.5 m in height, and pruned to an open vase.

Quantifying leaf and fruit development. Branch tips for leaf observations and fruit for measurement were selected for convenience of observation and labeled at about equal angles of growth and intervals around each tree at a height of about 2 m. In 1966 and 1971, 10 branch tips and 10 fruit on each of 5 trees were selected; in 1981, 5 branch tips and 3 fruit on each of 3 trees per cultivar were selected. Periods of observation were: April 16–July 18 in 1966, May 20–July 28 in 1971, and March 26–July 7 on 'Redhaven'; March 26–July 20 on 'Redglobe'; and March 26–August 19 on 'Rio-Oso-Gem' in 1981. Between 8 and 9 AM, the number of leaves completely unfolded were counted and leaves in the process of unfolding were scored on the basis of the scales shown in Fig. 1 for each branch tip. If older leaves abscised then, the current sum determined was not reduced since the daily change in youngest leaves was the essential datum desired.

Fruit were measured using a special device (Fig. 2). Small metric rulers were attached to opposite ends of a 2 × 5 × 10-cm wood block so that their divisions could be read simultaneously. The fruit, with suture oriented toward the observer, was placed between the rulers so that measurements were from cheek to cheek. Since repeat measurements involved contact of the device with fruit at the same point each day, extreme care was exercised to touch lightly in order to prevent injury. Measurements were read to the nearest 0.5 mm.

Growth rates were computed separately for leaves and fruit by the equation:

$$R = \frac{\sum a - \sum b}{Nt}$$

where:
R = the daily rate of leaf or fruit growth,
a = the current total number of leaves and fractional portion of the unfolding leaf, or the diameter of the fruit,
b = the previous day's total,
N = the number of branches or fruit observed,
t = the number of days between observations.

Sample size. Sample size needed to obtain a chosen precision was evaluated by calculating the variance (s^2) among growth rates of 50 branch tips for a randomly selected period (April 18–20, 1966) and applying the procedure devised by Stein (13) and elaborated by Steel and Torrie (12). It was calculated that 31 observations were required to obtain a precision of 0.1 leaf/day for leaf growth rate while 5 observations were required to obtain a precision of 0.25 mm for fruit diameter growth rate (Fig. 3).

Environmental data. Air temperature was read from a Belfort weekly recording hygrothermograph to the nearest 0.25°C; solar radiation was calculated in Langleys from a Belfort weekly recording pyrheliograph; and rainfall was read from a plastic, tapered rainguage to nearest mm. The hygrothermograph was located in a standard weather shelter and the pyrheliograph and

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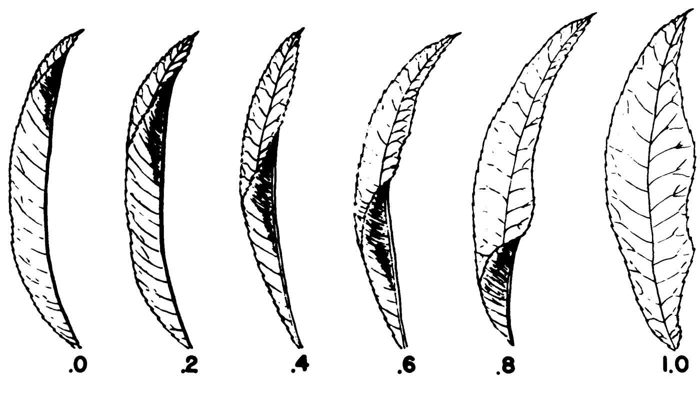

Fig. 1. Diagrammatic scale for quantifying morpholigic changes during leaf unfolding in peach. Illustration of even 10th-leaf stages that may be observed on the terminal leaf of each twig.

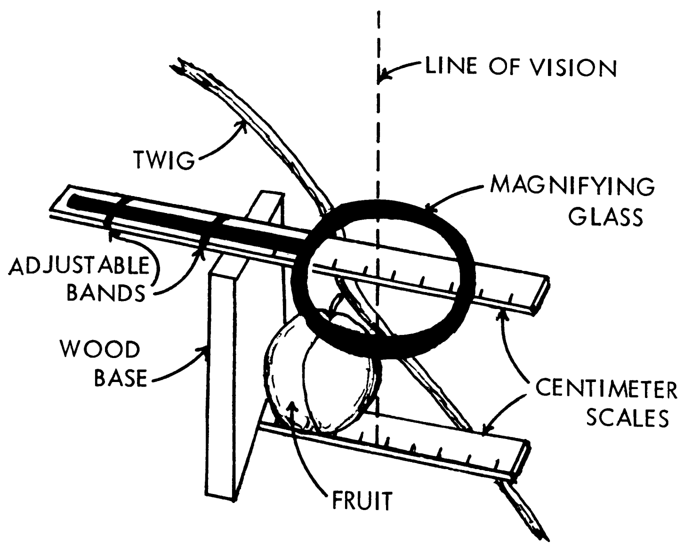

Fig. 2. Device used for daily fruit measurements.

rainguage were on the roof of the shelter. Also, a maximum-minimum thermometer and rain gauge, placed at a 2-m height within one of the observed trees, were used to ensure that recording instruments were accurately representing conditions within the canopy. Estimated soil moisture was computed by the Palmer-Havens adaptation (11) of the Thronthwaite-Mather method (14). By this method, daily precipitation is added to the storage capacity and evapotranspiration (read from tables) is subtracted.

Statistical analysis. To obtain generalized leaf and fruit growth prediction models, average daily growth rates for 3 cultivars in 1981 were regressed on the following basic daily variables: maximum and minimum temperature (°C), precipitation (cm), age (in days of leaf or fruit development) from mid-bloom, solar radiation (Langleys), degree hours above 15.6°, and estimated soil moisture (%) in upper 61-cm level. This temperature was used since 16° was the lowest level that maximum temperature reached during this growth period, and by selecting a base just slightly below this level no "0" values would be obtained for any days, and maximal arithmetic variation in degree-hours among days could be obtained. This procedure is in contrast to the traditional regression of cumulative leaf numbers on environmental variables, such as that of Eisensmith et. al. (5), who found a high degree of correlation of leaf number with degree-day accumulation. Lags (up to 3 days) and running 3-day sums in temperature and moisture variables were also included as "independent" (see later text for comment on independence of variables) variables. Additional variables to account for curvilinear effects were formed by transformations of the basic and lagged variables into the squares, cubes, and selected 2-factor cross products. A total of 108 independent variables were included in stepwise or multiple regression analyses performed with computer programs designed by the SAS Institute (1). In this program, growth rate was regressed on each "independent" variable individually and the one producing the highest R^2 was selected for the first step. In the next step, this variable was paired with all others to obtain the best R^2. These 2 were then combined with all remaining variables until an arbitrary limit of 15 was reached. From this relatively large number of variables, only a small number was represented in the step from which the prediction equation was selected. If the addition of a new variable

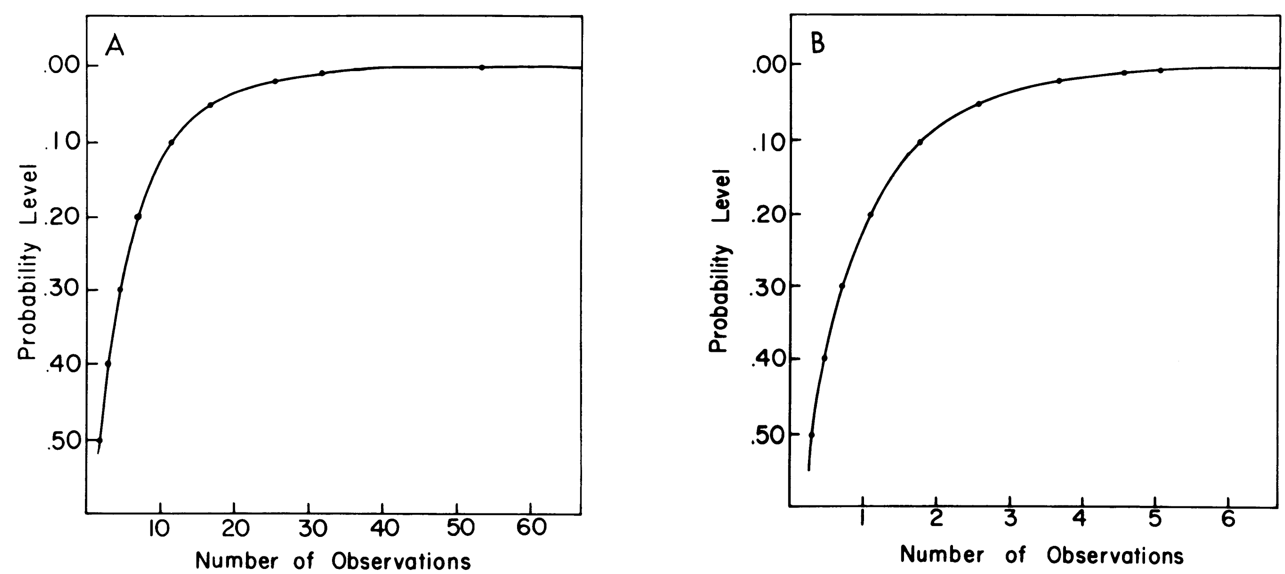

Fig. 3. Size of sample required to determine peach: (a) leaf growth rate with a confidence interval of ± 0.1 leaf/day; and (b) fruit diameter growth rate with a confidence interval of ± 0.025 cm/day.

caused the significance of a previously selected variable to fall below a given point, then the previous variable was rejected. Criteria used in selection of the best step for the leaf-growth prediction equation were R^2, significant Student's t, and F values. Since temperature, water (largely as "soil moisture"), and age are known to be functionally related to growth, but exact quantification of this relationship is unknown, stepwise multiple regression analyses was made to obtain a useful set of coefficients and transformations of the variables. Further, the outcome of the analysis was based not only on significant statistical indications but also on a successful test of the prediction equation on independent (unrelated) data. Since there is intercorrelation among variables, it is not possible to assign a rigid order of significance among them; it may be generalized that those selected were, as a group, relatively more important statistically than others in the 108.

Results and Discussion

Fig. 4 presents the day-to-day variations in leaf and fruit growth rates and their cumulative increases for 3 cultivars in 1981. The cumulative fruit growth (diameter) curves resemble those of Tukey (15) for the pericarp of 4 other cultivars, although he made no use of the growth rate that could have been based on samples at 2-day intervals. A comparison of lowered fruit growth rates during Stage II (4) may be made in this figure. The relatively short period for 'Redhaven' extends from about May 15 until June 5 (Fig. 4a). A period of intermediate length for 'Redglobe' extends from about May 15 until June 25 (Fig. 4b), and the longest period for 'Rio-Oso-Gem' (Fig. 4c) extends from about May 15 until July 10. The period of Stage I was quite similar among the 3 cultivars as was found by Tukey (15) on other cultivars. Differences in length of Stage II were obviously related to the date of fruit ripening.

Comparisons of daily leaf growth rates of the 3 cultivars by overlaying their graphs also revealed striking similarity of fluctuations. This similarity was further accentuated by construction of 3-day running averages of the 3 cultivars (Fig. 5). Two conclusions can be drawn from this presentation: 1) quantitative morphological observations may be used to detect small daily changes in peach leaf growth rate; and 2) effects of weather variations on leaf growth rate are quite similar among cultivars. The more vigorous vegetative growth of 'Redhaven' is evidenced by the fact that its growth rate is slightly greater than the other cultivars on many days of the season.

Growth-environment relationships were determined by regressing rates of leaf (Table 1) and fruit growth (Table 2) on the recorded environmental variables (Fig. 6) and their transformations (squares, etc.) and interactions (products). In the step-down analyses of leaf growth rate, the inclusion of solar radiation and degree hours above 15.6°C resulted in little or no improvement of R^2 values; therefore, they were excluded in subsequent analyses. This does not preclude the possibility that useful models could be constructed with these variables. However, since these variables are not routinely published for most weather stations and one of the chief objectives of this research was to develop models that could be applied to commonly published weather data for predicting potential yields as the season progresses, they were excluded from analyses reported here. It is of interest that precipitation was significant in the leaf growth analysis (Table 1), but not in the fruit growth analysis (Table 2), otherwise the same basic variables appeared in both. This may reflect the relatively greater exposure of leaves to effects of precipitation. The minor or secondary importance of the solar radiation variable (relative to leaf number) is potentially similar to that reported for apple trees (2, 3). However, this does not necessarily imply the absence of importance for solar radiation, since daily amounts in the geographical locations involved generally may be well in excess of critical levels.

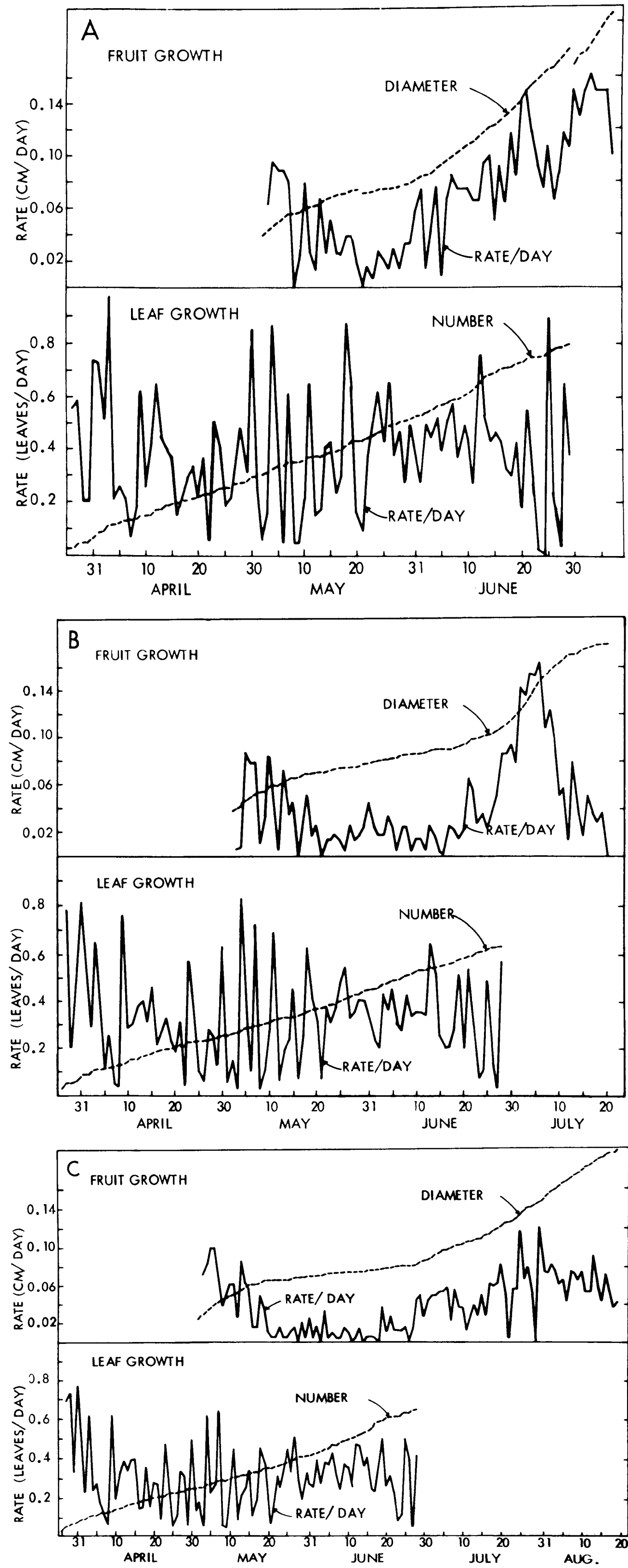

Fig. 4. Leaf and fruit growth of 3 peach cultivars in 1981: (a) 'Redhaven', (b) 'Redglobe', and (c) 'Rio-Oso-Gem'.

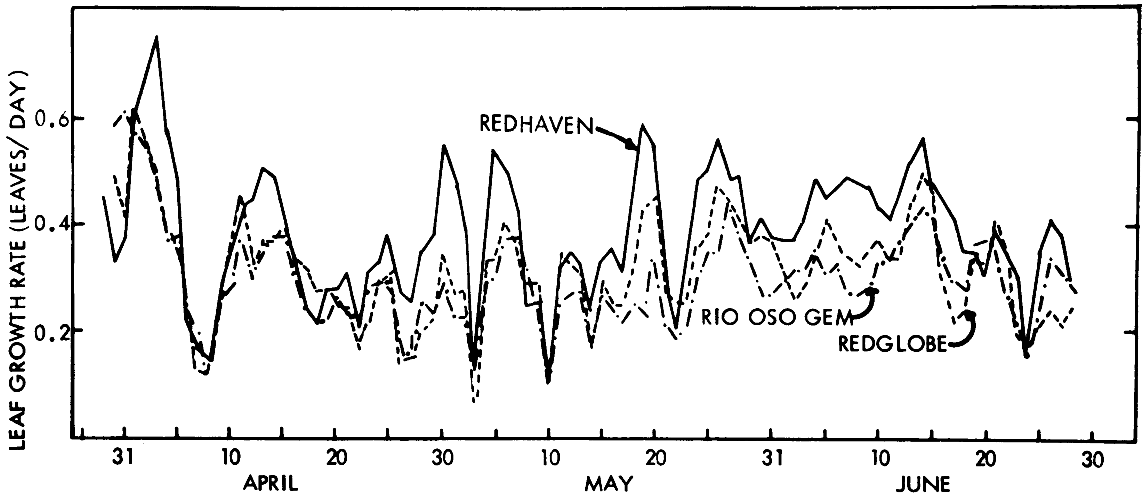

Fig. 5. Leaf growth rates (3-day running average) of 3 cultivars in 1981.

Table 1 presents statistics for one of the best steps in the multiple regression analysis of leaf growth rate considering: F highly significant with 76 degrees-of-freedom for error, all "independent" variables with significant Student's *t* values, and an R^2 of 0.679. Coefficients for the leaf growth-rate-prediction equation are also given in Table 1 as follows: Leaf growth rate = 0.92 − 0.0333 × Age + 0.000878 × Age^2 . . . etc. "Predicted" (i.e., calculated) values were compared to the actual data on which the leaf growth-rate-prediction equation is based (Fig. 7) and to a portion of a different season and different cultivar, 'Redskin' (Fig. 8). Similarly, fruit growth rate and predictions were compared for the data on which the prediction equation was based and to independent data (Table 2, Fig. 9 and 10). The reason actual growth rates of 'Redskin' fruit are slightly lower than predicted is probably that the average date of maturity for 'Redskin' is slightly later than the average of the 3 cultivars on which this model is based.

Rationale for this approach is that, in the absence of specifically quantified plant-environment relationships that can be used in growth prediction systems, it provides a means for: 1) establishing useful methematical values for *daily* plant responses to environmental factors, under natural uncontrolled conditions; and 2) computer search of many empirically selected transformations of basic variables known to be important, such as temperature, soil moisture, and their potentially delayed effects over several days. Although statistics of fit for the multiple regression analyses are significant, they should not be considered alone as evidence of applicability of prediction equations. Since the statistical prerequisites for analyses of this type can never be completely met (e.g., there should be no intercorrelation of

Table 1. Analysis of variance, regression coefficients, and statistics of fit for the dependent variable average (3-day running) daily leaf growth rate of 3 peach cultivars at Clemson, S.C., 1981.

Source	df	MS	F	Prob. F	R^2
Regression	10	0.04901	16.09	0.0001	0.679
Error	76	0.00304			
Total	86				

Variables	Partial regression coefficients	Prob. > | *t* |
Intercept	0.92	
Age[z]	-3.33×10^{-2}	0.0001
Age^2	8.78×10^{-4}	0.0001
Age^3	-5.60×10^{-6}	0.0001
PR[y]	-4.40×10^{-2}	0.0496
PR^2	1.50×10^{-2}	0.0086
ESM[x] 1-day lag	-9.92×10^{-3}	0.0001
Age × (ESM 2-day lag)	-4.16×10^{-5}	0.0013
Age × (Min[w] temp 1-day lag)	1.14×10^{-4}	0.0046
Age × (Max temp 1-day lag)	-2.55×10^{-4}	0.0001
(ESM 1-day lag) × (Max temp 1-day lag)	3.47×10^{-4}	0.0001

[z]Days from 50% full bloom.
[y]PR = Running 3-day sum of precipitation plus irrigation (cm).
[x]ESM = Estimated soil moisture (%) Thornthwaite - Mather method.
[w]All temperatures (°C).

Table 2. Analysis of variance, regression coefficients, and statistics of fit for the dependent variable average (3-day running) daily fruit growth rate of 3 peach cultivars at Clemson, S.C., 1981.

Source	df	MS	F	Prob. F	R^2
Regression	11	0.004817	53.11	0.0001	0.865
Error	91	0.000091			
Total	102				

Variables	Partial regression coefficients	Prob. > | *t* |
Intercept	0.05	
ESM[z]	-8.30×10^{-3}	0.0001
ESM^2	7.83×10^{-5}	0.0001
ESM^3	-3.51×10^{-7}	0.0001
Min temp[y]	-6.84×10^{-3}	0.0001
Min temp^2	2.28×10^{-4}	0.0001
R[x] max temp	4.03×10^{-3}	0.0001
Max temp 1-day lag^2	-6.82×10^{-5}	0.0001
Max temp 2-day lag^3	-1.75×10^{-6}	0.0001
Max temp 3-day lag^3	-1.84×10^{-6}	0.0001
Age[w] × min temp	-3.70×10^{-5}	0.0001
Age × ESM	3.84×10^{-5}	0.0001

[z]ESM = Estimated soil moisture (%) Thornthwaite - Mather method.
[y]All temperatures (°C).
[x]R = Running 3-day sum of Lag 1 + Lag 2 + Lag 3.
[w]Days from mid-bloom.

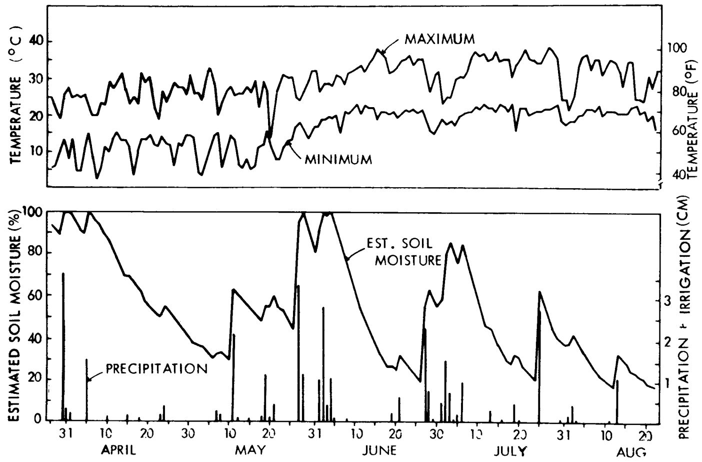

Fig. 6. Temperature, rainfall, and soil moisture for peach trees measured in 1981.

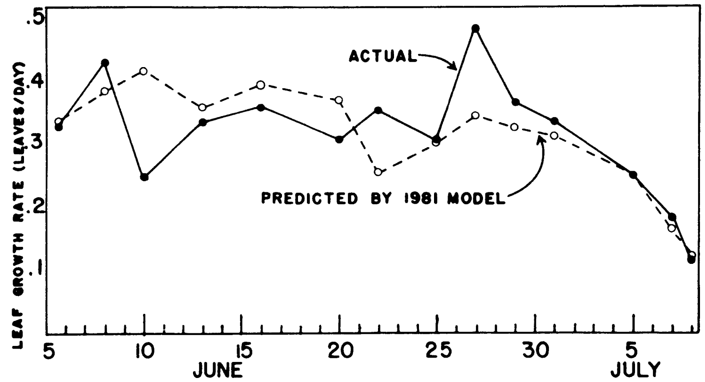

Fig. 8. 'Redskin' leaf growth rate in 1966 and growth rate calculated by prediction equation for 3 cultivars in 1981 (Table 1).

"independent" variables such as temperature and soil moisture), their validity is established by tests on unrelated data. Regression analysis is not considered as a "modeling" procedure *per se*, but simply as a logical and convenient means for quantifying relationships of measured variables. The similarities in magnitude and variations (Fig. 8 and 10) of actual growth rates (of 'Redskin' in 1966 and 1971) and growth rates predicted by the prediction equations indicate that the models based on 3 cultivars (in 1981) are capable of generalizing the response of peach to environmental variables involved in these analyses. If more precise predictions for individual cultivars are desired, models can be developed by restricting basic growth data to the cultivar of interest, or possibly by normalizing varieties' period of fruit growth to substitute for calendar days. Subsequent applications of the generalized model will be directed toward development of systems to predict harvest dates, yields, and quality utilizing this method for quantifying growth responses to weather and environmental conditions as has been demonstrated for corn (9).

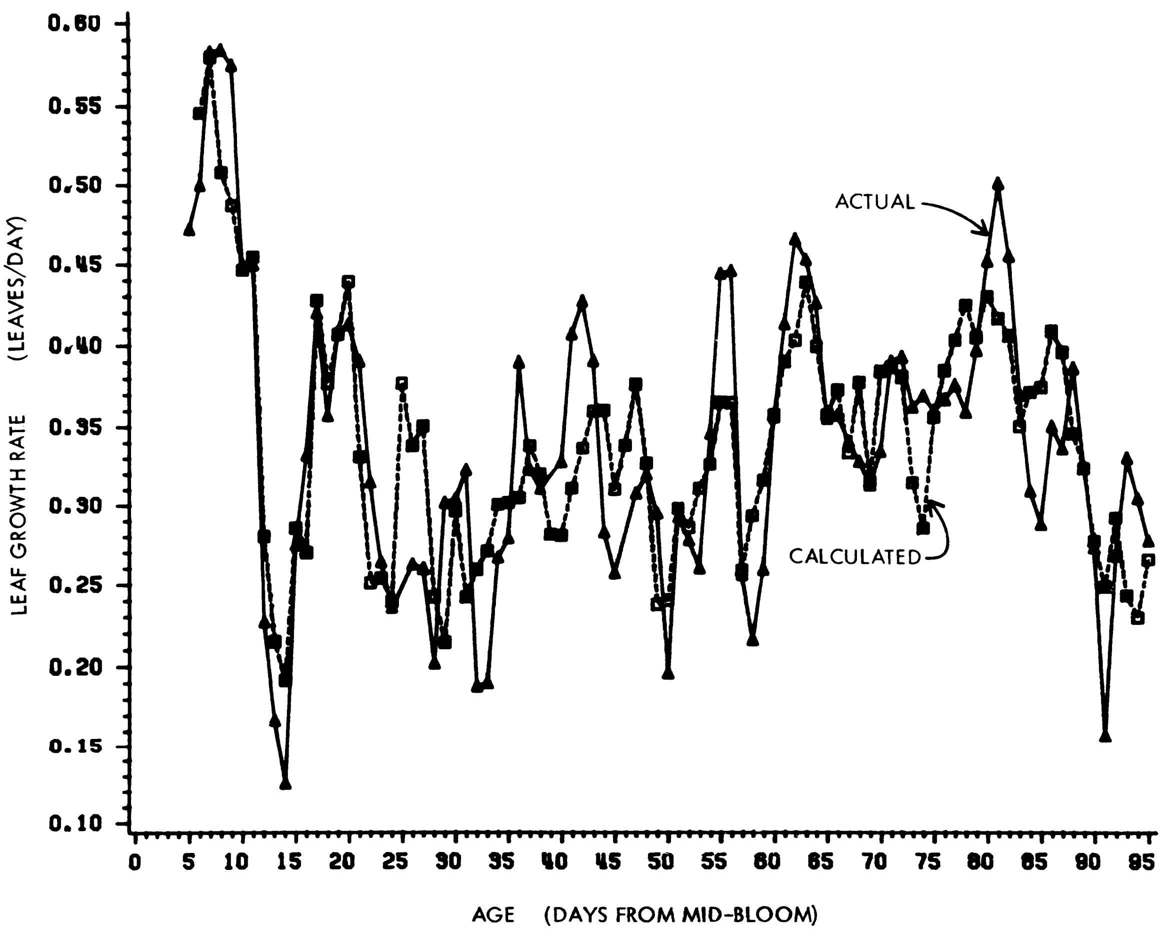

Fig. 7. Average leaf growth rates (3-day running) and leaf growth rates calculated by prediction equation (Table 1) for 3 cultivars, 1981.

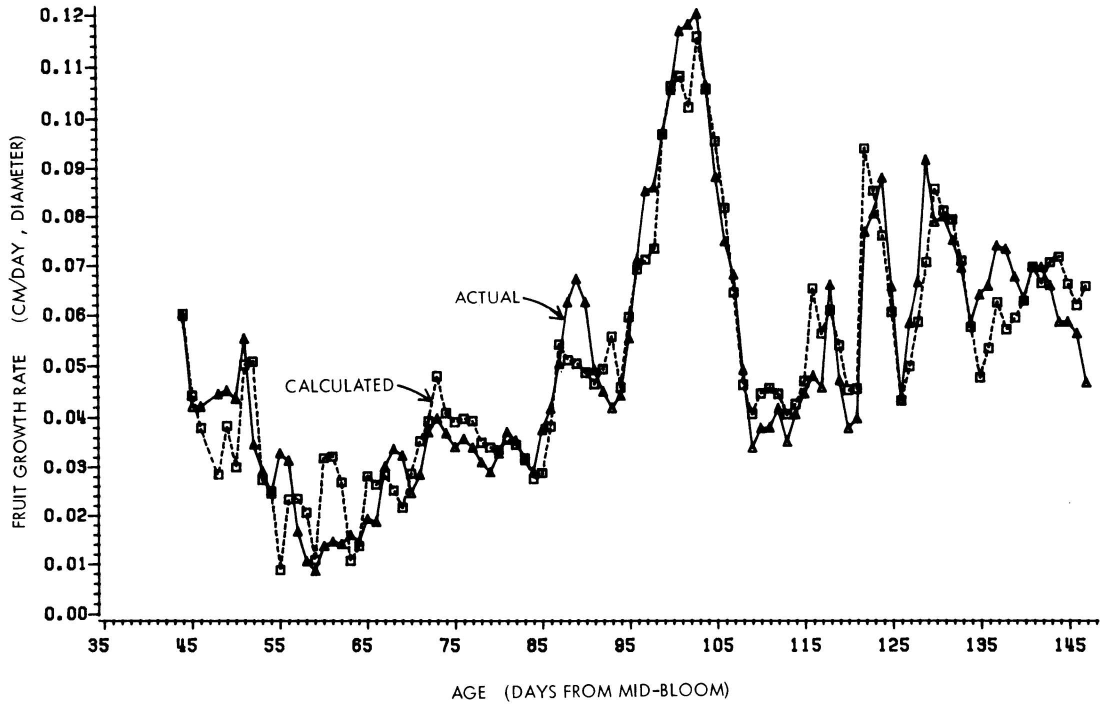

Fig. 9. Average fruit growth rates (3-day running) and fruit growth rates calculated by prediction equation (Table 2) for 3 cultivars, 1981.

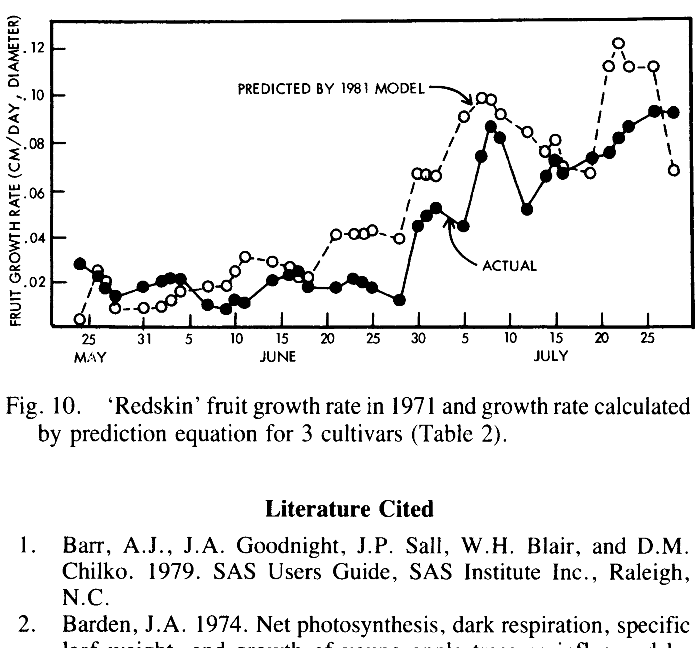

Fig. 10. 'Redskin' fruit growth rate in 1971 and growth rate calculated by prediction equation for 3 cultivars (Table 2).

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