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DEPARTMENT OF COMMERCE ★ UNITED STATES OF AMERICA ★

ON THE USE OF SOLAR RADIATION AND TEMPERATURE MODELS TO ESTIMATE THE SNAP BEAN MATURITY DATE IN THE WILLIAMETTE VALLEY

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National Weather Service
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ON THE USE OF SOLAR RADIATION AND TEMPERATURE MODELS TO ESTIMATE THE SNAP BEAN MATURITY DATE IN THE WILLAMETTE VALLEY

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I. INTRODUCTION

Because of the importance of meteorological factors on the geographical distribution of plants and on their reproductive cycle, there has been considerable interest in using meteorological and climatological data to explain the growth and development of plants. This has lead to the slow evolution of increasingly complex models which are now being used by ecologists, horticulturists and vegetable processing companies to explain, with varying degrees of success, how such variables as temperature affect plant growth and maturity.

In the Willamette Valley of western Oregon, an important vegetable crop is snap beans *(Phaseolus vulgaris L.)*. During the three-year period 1975-1977, the average annual value of snap beans to growers was 19.0 million dollars ($144/ton and 4.4 tons/acre) (OSU Extension Service, 1979), and the value added by processing amounted to about 50 million dollars.

In order to insure that processors have an orderly flow of snap beans into the processing plants, planting dates must be established and scheduled so that there are successively maturing crops in harvest season. Thus, if a method based on climatological variables is available to estimate the date of maturity, using the desired schedule of harvest dates, it is possible to determine dates needed to meet this harvest schedule. The heat-unit model has had some use in the Willamette Valley for this type of crop management. The heat-unit model, however, is generally considered to be unreliable for this purpose. This is especially true for crops harvested late in the crop year.

The purpose of this preliminary study was to use available phenological and climatological data in evaluating some of the available models to see if the heat unit model could be improved or a better model developed.

II. THE PHENO-CLIMATOLOGICAL MODELS

René A. F. deRéaumur (c. 1740)[1] suggested what was probably the first and certainly the simplest pheno-climatological model of plant development. It can be expressed by the following equation which integrates the ambient temperature $T(t)$ between planting time t_p and the time of maturity t_m as

[1]The inventor of the temperature scale which bears his name. On this scale 0°R is the melting point of ice and 80°R is the boiling point of water.

follows:

$$\int_{t_p}^{t_m} T(t)dt = k_o, \qquad (1a)$$

where $T(t) \equiv 0$ if $T(t) < 0$ and k_o is a varietal constant (degrees - unit time).*

The subsequent development of the concept of a threshold temperature necessary to sustain growth in a plant lead to the following, "heat unit" model which has been used since the time of Boussingault (1837):

$$\int_{t_p}^{t_m} (T(t) - a_1)dt = k_1, \qquad (2a)$$

where $(T(t) - a_1) \equiv 0$ if $T(t) < a_1$ and k_1, which is just the integrated departure of temperature from a reference value, is a varietal constant (degrees - unit time). The reference value a_1 is another varietal constant which is usually called the basis.

In applied studies, it is always necessary to approximate the integrals in Eqs. 1 and 2 (or in any other model for that matter) by summations over some finite increment of time. Most commonly, as is done in this study, the summations are by day. If T_m is the daily average temperature, P the planting date and M the date of maturity, then these two models become:

$$\sum_{P}^{M} T_m = k_o, \qquad (1b)$$

where $T_m = 0$ if $T_m < 0$ and k_o has the units of degree-days: and

$$\sum_{P}^{M} (T_m - a_1) = k_1, \qquad (2b)$$

where $(T_m - a_1) = 0$ if $T_m < a_1$ and k_1 has the units of degree-days or

*Note: The k varietal constants, as discussed in this paper, are constants for this particular location. If used elsewhere, these sight-specific constants would be different.

the number of growing degree days (GDD).[2,3] Furthermore, in biometeorological applications, the daily mean temperature T_m is often approximated by using the mid-range temperature (one half the sum of the maximum and minimum).[4] This is convenient and often necessary because the maximum and minimum temperatures are all that are observed at most stations in the national climatic grid. The nomenclature of biometeorology is sometimes confusing because the mid-range temperature is usually called the mean daily temperature.

In the heat-unit model, Eq. (2), the effects of all factors besides temperature are absorbed into one constant, the basis a_1. Therefore, the problem seems to be oversimplified; and there have been several attempts to remedy this apparent defect. Nuttonson (1958) included the effects of photoperiodism by multiplying the heat-unit model by the average day length $\overline{L}$ during the growing period, i.e.,

$$\overline{L} \sum_{P}^{M} (T_m - a_2) = k_2 \tag{3}$$

where $\overline{L} = \frac{1}{M-P} \sum_{P}^{M} L$ and $(T_m - a_2) \equiv 0$ if $T_m < a_2$ and k_2 is called a thermal unit (PTU). The basis a_2 for this model is not necessarily identical to the basis a_1 in Eq. (2). Although this model seems to be much better than the heat-unit model at various localities with widely separate latitudes, it was also an improvement[5] in the case of Marquis wheat grown during different time intervals of a given crop year (Nuttonson, 1958).

Another crop model was developed by Caprio (1971). He found that the heat-unit model could be improved if the amount of total daily solar-radiation (global, the sum of the direct and diffuse) measured on a flat

---

[2]These are also called accumulated heat units (AHU) by some authors.

[3]If the summation in Eq. (2a) is done for each hour, then T_m is some hourly temperature value (e.g., from some source as a NWS 1st order station), or $\Sigma (T_m - a_1)$ is the area under a thermograph trace above the basis. In this case, k_1 is called the number of growing degree hours (GHD). Naturally better results are reported in the literature for GHD's because it is a better approximation to Eq. (1a).

[4]A discussion of the effects of using a long-term daily mean temperature which does not take into account the variability of the weather can be found in Chen (1973).

[5]In the sense that the coefficient of variation for k_2 was 7.8% compared to 11.4% for k_1 for a test case of Marquis wheat at Moro, Oregon, sample size 17.

surface Q_T(ly[6]) was included in a model in the following way:

$$\sum_{P}^{M} Q_T(T_m - a_3) = k_3, \qquad (4)$$

where $(T_m - a_3) \equiv 0$ if $T_m < a_3$, k_3 is called a solar thermal unit (STU).

Caprio viewed the inclusion of Q_t as an effective way to adjust for the climatological inhomogeneitites which existed among geographic areas.

In response to various complaints about the apparent inadequacy of the heat-unit model when used with Willamette Valley crops, Bates (1976) suggested the following simple model based solely on the daily accumulation of total solar radiation received:

$$\sum_{P}^{M} Q_T = k_4 \qquad (5)$$

where k_4 is a varietal constant with units of langley.[7]

In this study, two new models were also tested. The first is called the radiation-temperature model. It is the following combination of daily total-solar-radiation and the daily maximum and minimum temperatures:

$$\sum_{P}^{M} Q_T \frac{T_{max} - a_4}{a_5 - T_{min}} = k_5 \qquad (6)$$

where a_4, a_5 are two parameters to be fitted to a particular data set (in this preliminary study, for brevity just 32°F (0°C) and 100°F (37.8°C) are used for a_4 and a_5 respectively.

The second is called the statistical model. It is a statistical analog to an equation derived in Appendix A, which has the following form:

$$\sum_{P}^{M} (T_m - a_6) + a_7(Q_T/L) + a_8(M - P) = k_6 \qquad (7_a)$$

[6] A langley (ly) is equal to one gram-calorie per square centimeter or 4.186 joules per square centimeter.

[7] The proportion of photosynthetically active radiation (PAR) in sunlight does not vary significantly with time of day, time of year or with atmospheric conditions (Williams, 1976).

where a_6 is the basis, a_7, a_8 and k_6 are three additional varietal constants and the variable $(M - P)$ is the number of days to maturity. The basis a_6 is not necessarily the same as the basis a_1 of equation (2). To get the statistical model which follows, equation (7a) is treated as a linear 1st order regression model and grade information is included as a third independent variable:

$$(M - P)_i = \beta_0 + \beta_1 \left[\sum_P^M (T_m - a_6)\right]_i + \beta_2 \left[\sum_P^M (Q_T/L)\right]_i = \beta_3 \left[G_{1,2}\right]_i + \varepsilon_i \quad \text{(7b)}$$

where:

$(M - P)_i$ are the number of days to harvest for the ith trial,

β_0, β_1, β_2, and β_3 are parameters of the model (regression coefficients),

$\left[\sum_P^M (T_m - a_6)\right]_i$, $\left[\sum_P^M Q_T/L)\right]_i$ and $\left[G_{1,2}\right]_i$ are the values of the the independent variables at the ith trial. $\left[G_{1,2}\right]_i$ is the percentage of the ith crop that was Grades 1 and 2 combined, and the other variables were defined previously.

ε_i is the usual random error term,

$i = i, \ldots,$ n where n is the sample size.

a_6 is assumed to be the same as the basis a_1 of Eq. (2).

III. THE SNAP-BEAN PHENOLOGICAL RECORDS

In February of 1979, data on snap-bean crops were acquired from both the Eugene and Salem offices of Agripac, Inc., the Salem office of Libby, McNeill & Libby, Inc., the Albany office of Stokely-VanCamp, Inc., Dr. H. Mack, Oregon State University horticulturist, and Dr. J. Vomocil, Oregon State University soil scientist. The raw data totaled 747 different snap-bean crops which had been planted in western Oregon. There were 15 different varieties of beans. The earliest data was from the 1969 season and the latest from the 1978 season.

The crop information was first edited according to the following specifications:

a. The fields had to be located in the Willamette Valley;

b. Grade information[8] had to be available unless the data were from an OSU experimental plot (e.g., the Vomocil data);

c. The percentage of the crop that was in Grades 1 and 2 combined had to be at least 20%;

d. The harvest had to have been completed in one day.

The crop information was then stratified by geographical areas within the Willamette Valley (Fig. 1) which were defined as follows:

a. Area 1 (the Eugene Area) - a band across the valley from Belt Line Road, Eugene northwards to the city of Harrisburg;

b. Area 2 (the Corvallis area) - a band across the valley from the city of Harrisburg northwards to the city of Buena Vista:

c. Area 3 (the Salem area) - a band across the valley from the city of Buena Vista northwards to the city of Gervais:

d. Area 4 - the northern end of the valley.

Next, these crops were stratified by variety. Only for Oregon 1604 and Asgrow 290 varieties were there enough data to get samples large enough to attempt further analysis. Also, since the success of the heat-unit model seems to depend on seasonally changing variables, the planting dates were stratified by seasons which are defined for the purposes of this study as:

a. Early - 1 May through 14 May;

b. Middle - 15 May through 8 June;

c. Late - 9 June through the last planting date (7 July).

The breakdown by planting season was based mostly on experience with response of this crop to the climate of this valley; however, it was also based in part on an effort to get both reasonable sample sizes in each category and some differentiation among the harvest periods.

The final snap-bean sample sizes by area, variety and planting season are shown in Table 1. A further breakdown of the Eugene Area data by year is shown in Table 2. Even in this case, there are insufficient data to study adequately any interannual variations. A good pheno-climatological model will have little variation in its constant (e.g., k_1, Eq. (2)). What appears to be needed for this is sample sizes of about 30 in each category of Table 2.

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[8] Grade 1 is sieve sizes 2 and 3, Grade 2 is sieve size 4, Grade 3 is sieve size 5, Grade 4 is sieve size 6 and the culls are sieve sizes 1 and 7.

Table 1. Sample sizes n for the snapbean phenological data used in this study when stratified by area, variety, and planting season.

Planting Season*	Grade(s)	Salem Area Data (1978) Variety 1604*	Salem Area Data (1978) Variety 290**	Eugene Area Data (1973-1978) Variety 1604@	Eugene Area Data (1973-1978) Variety 290#
Early	1	13	0	20	5
	2	13	0	20	5
	3	13	0	20	5
	4	13	0	20	5
	1 & 2	19	4	20	5
	3 & 4	19	4	20	5
	culls	19	4	20	5
Middle	1	17	31	8	28
	2	17	31	8	28
	3	17	31	8	28
	4	17	31	8	28
	1 & 2	20	34	8	28
	3 & 4	20	34	8	28
	culls	20	34	8	28
Late	1	0	29	0	27
	2	0	29	0	27
	3	0	29	0	27
	4	0	29	0	27
	1 & 2	0	29	0	27
	3 & 4	0	29	0	27
	culls	0	29	0	27

*Defined in the text

**Libbey's data did not include information on Grades 1 through 4.

@All data on the early plantings of variety 1604 are from 1976 through 1978. The unanalyzed data on midseason plants are spread over 5 years.

#One late planting of variety 290 has no grade information (Vomocil data).

Table 2. Number of Eugene Area plantings stratified by variety, year and planting season.

Year	Variety/Planting Season 1604/Early	290/Middle	290/Late
1973	0	2	2
1974	0	3	6
1975	0	7	9
1976	9	7	0
1977	3	7	7
1978	8	2	3

Figures 2 and 3 show the number of dates of the plantings and harvests by area, variety and planting season. The overall pattern is one of a narrow planting period and an associated harvest period that is somewhat longer. One problem with these data when used in a study of this type is best illustrated by the late June plantings of Asgrow 290 in the Salem area in 1978 (Fig. 2). Here a large number of fields (10) were planted on one day, but they were subsequently harvested over a period of a few days late in August. This shows an apparently large influence of cultural practices on the harvest dates - such factors are outside the scope of this study.

Figure 2 also shows the daily rainfall amounts reported at the Salem Airport (SLE). It should be noted that after a very rainy period during the middle of the month of May, there was a flurry of plantings. Then again, in August of this year, it was necessary to harvest in the rain. This is an example of a meteorological variable which has not been included in this study influencing cultural practices.

Table 3 shows statistics on the number of days to harvest and the correlation between the harvest dates and the percentages of each crop in Grades 1 and 2 combined. One approach to estimating harvest dates is to use the average number of days to harvest. These data suggest that, with such an approach, the root-mean-square error (RMSE) may be as high as 5 days. Any type of practical pheno-climatological model for plant maturity must be better than this.

The correlation coefficients in Table 3 point out another problem or limitation of these data sets. Pheno-climatological models for plant maturity are to be tested, yet sometimes a large fraction of the total variation in the number of days to harvest is accounted for by quality or grade of the crop harvested, indicating that the harvests are not always scheduled for a standard grade. This is a non-meteorological factor. In this study, only Eq. (7b), the statistical model, is capable of including grade information as one of the variables. An objective method for adjusting harvest date to a standard percentage by grade would be very useful.

Table 3. The mean number of days to harvest, the standard deviation and the corelation between the percentage of each crop in grades 1 and 2 combined and the number of days to harvest

Area	Variety	Planting Season	No. of Days to Harvest Mean	Std. Dev.	Correlation Coefficient
Salem	1604	Early	78.6	±2.2	-0.89
	1604	Middle	71.3	±2.0	-0.16*
	290	Middle	77.6	±4.4	-0.37
	290	Late	71.3	±2.2	-0.06*
Eugene	1604	Early	78.0	±3.7	-0.13*
	290	Middle	78.5	±5.0	-0.70
	290	Late	76.2	±5.2	-0.35

* Not significantly different from 0 at the 5% level

IV. THE CLIMATOLOGICAL DATA

The Willamette Valley's general location and topographic complexity is shown in Fig. 1. It is a large area enclosed by the Cascade Range (on the average 6500-ft (2 km) high) to the east and the Coast Range (on the average 1600-ft (0.5 km) high) to the west. At the falls of the Willamette, near Oregon City, and south of Eugene, the ends of the valley are closed by the juncture of these two mountain ranges. The valley floor, where the vegetable crops are grown, is about 31-miles (50 km) wide and about 110-miles (185 km) long, and it descends gradually from an elevation of about 360 ft (110 m) to less than 130 ft (40 m) near Oregon City at the north end of the agricultural area. The floor is nearly level in some places, gently rolling in others and broken by several groups of hills and scattered buttes.

During the summer, the winds are generally light and northerly, but there are up-and down-slope winds and sea breezes. The sea breezes or penetrations of cool, marine air through the gaps in the Coast Range lower the temperatures in the valley and make the mid-range temperatures a less accurate approximation of the true average daily temperature.

Figure 1 also shows this study's 4 snap-bean growing areas within the Willamette Valley. For Area 1, the temperature data were observed at the National Weather Service first order station at the Eugene Airport (EUG) which has a station elevation of 359 ft (109.4m) above mean sea level (MSL). For Area 2, the temperature data were observed at the National Weather Service Climatological Observatory at the Hyslop Agricultural Field Laboratory, Oregon State University (COV) 225 ft (68.8m) MSL. This station is not shown on Fig. 1, but it is 10 miles (16.1 km) NNE of the Corvallis Airport (CVO). For Area 3, the temperature data were observed at the National Weather Service first order station at the Salem Airport (SLE) which has a station elevation of 196 ft. (59.7 m) MSL. The distances involved are: SLE to EUG, 56 miles (90.1 km); COV to EUG, 35.5 miles (57.1 km); and COV to SLE, 21.8 miles (35.1 km). The maximum and minimum thermometers are all at standard shelter heights ($\sim$1.5 m above ground).

The solar radiation data from the Eugene Area have a period of record (POR) of 1975 - 1977. The instrument is located on top of the Physics Building of the University of Oregon, Eugene, Oregon. The 1975 - 1976 data were collected using an Eppley PSP Pyranometer, and the 1977 data with a Schenk Star Pyranometer. The COV radiation data have a POR of 1969 - 1978. The instrument is a Belfort pyrheliograph colocated with the thermometers at COV at an instrument height of $\sim$ 1.7 m. Strip charts from both locations are routinely reduced to values of total daily solar radiation Q_T.

Climatological observations such as these are not the same as observations taken in the plant habitat itself, and all microclimatic variations are necessarily ignored. However, one objective of this study is to use standard climatological data which can easily be made available to agriculturalists.

A climatological data file was constructed for the period 1 May through 31 August for each of the years 1969 through 1978. This data file included all maximum and minimum temperatures, the Corvallis radiation data, the Eugene radiation data when available and the day length at Corvallis. The maximum variation in day length within Areas 1 through 3 of the Willamette Valley is only about 3 minutes.

The degree-day requirements for a given variety are known to decrease with increasing altitude (e.g., Nuttonson, 1958). This should have little effect on this study because the altitude variation is negligible within the valley (see also the discussion in Hennessey, 1979, and in the literature cited therein).

In this preliminary study, only a cursory examination of the climatology was possible. Table 4 includes the summary statistics for the differences in the maximum, minimum and mid-range temperatures among these three stations. On the average, these differences are rather small; and the use of the mid-range temperature tends to decrease the variation about the mean. The usual argument is that, when one is dealing with accumulations of temperatures over several weeks, any difference between stations within an area as small as this valley will be averaged out. Figure 4 shows the test of this hypothesis using the snap bean samples from the Eugene Area (see Table 1 and Fig. 3). [Note: both Fig. 4 and 5 are "box and whisker" plots. The "box" is centered at the mean of the sample and extends ±1 standard deviation either side. The "whiskers" extend from the ends of the box to the minimum and maximum sample values (unless the data are so badly skewed that one of the extremes is within 1 standard deviation of the mean).]

In Fig. 4, summary statistics on the differences in the accumulated mid-range temperatures among these three stations as percentage of the accumulated COV mid-range temperature are depicted by the box and whisker plot. These mid-range temperature accumulations (i.e., k_o, Eq. (1)) are between the planting and harvest dates for the snap-bean data from the Eugene Area (Table 1 and Fig. 3). On the average, the mean differences are about 1 - 2%, and the variance increases with increasing distance between stations. A similar analysis (not shown) for the Salem Area data, which are all from just one year, shows the mean differences ranging from about 1/2 to 4%, but the standard deviations less than ±1/2%. Thus, the conventional wisdom is confirmed, at least by these data; and the use of one temperature reporting station from each area appears justified.

Table 4. Descriptive statistics for differences in maximum, minimum and mid-range (°F) among the three observation sites used in this study, POR 1969 - 1978. (The temperature differences are computed by subtracting the value at the southern site from the value at the northern site.)

Type of Temperature Difference	COV - EUG			SLE - COV			SLE - EUG		
	Mean	Std. Dev.	Range	Mean	Std. Dev.	Range	Mean	Std. Dev.	Range
Maximum	-1.6	±2.3	-14,13	1.0	±1.7	-5,9	-0.6	±2.8	-14,22
Minimum	-0.1	±4.0	-16,19	-0.6	±3.9	-24,25	-0.8	±3.5	-15,32
Mid-range	-0.9	±2.4	-10,10	0.2	±2.1	-11,13	-0.7	±2.3	-10,16

There have historically been few climatological analyses of solar radiation data in spite of its being the prime factor of climate (Griffiths, 1975), and little time was available for such analyses during this study. However, for all 333 days during 1975 - 1977 with simultaneous radiation observations, the correlation between total daily radiation observed at the University of Oregon ($Q_{T\ UO}$) and the total daily radiation at COV ($Q_{T\ COV}$) is 0.87; and 76% of the variance is explained by the following linear regression model:

Table 5. The mean and standard deviation (in parentheses) for each model's summation (k) for each snap-bean sample (Table 1).

		Variety/Planting Season			
Area	Model	1604/Early	1604/Middle	290/Middle	290/Late
Salem	Réaumur	4935 (199)	4710 (142)	5250 (244)	4904 (138)
	Bates	35588 (1538)	34204 (1066)	37979 (2014)	32328 (981)
	Nuttonson (45°F)	20826 (1159)	22608 (823)	26356 (923)	24876 (589)
	Nuttonson (50°F)	19601 (1123)	21484 (795)	25142 (873)	23786 (555)
	Heat Unit (45°F)	1352 (76)	1457 (55)	1712 (61)	1645 (42)
	Heat Unit (50°F)	958 (65)	1097 (46)	1320 (48)	1287 (32)
	Caprio (45°F)	642637 (43266)	718554 (29813)	854337 (34225)	765085 (16713)
	Caprio (50°F)	466486 (36561)	547993 (24691)	664698 (26684)	603447 (12252)
	Rad-Temperature	29152 (1917)	31562 (1230)	37265 (1608)	33057 (739)
	Statistical (none)	-1961 (24)	119 (12)	-774 (23)	-608 (14)
	Statistical (45°F)	-2372 (50)	-300 (11)	-11542 (577)	-649 (18)
Eugene	Réaumur	4688 (247)		5109 (313)	5104 (364)
	Bates	35420 (1887)		38430 (2403)	35751 (2550)
	Nuttonson (45°F)	17482 (1243)		23450 (1882)	24150 (2005)
	Nuttonson (50°F)	16268 (1183)		22229 (1850)	23006 (1952)
	Heat Unit (45°F)	1133 (83)		1530 (132)	1629 (146)
	Heat Unit (50°F)	752 (64)		1134 (119)	1243 (125)
	Caprio (45°F)	546702 (46877)		771488 (82407)	786277 (76167)
	Caprio (50°F)	373937 (36524)		579756 (72901)	607519 (64458)
	Rad-Temperature	28987 (2282)		37856 (3597)	37799 (3598)
	Statistical (none)	344 (26)		1779 (117)	601* (69)
	Statistical (45°F)	-897 (83)		-9049 (323)	1452* (114)

*26 with grade information

$$Q_{T,UO} = 73.8 + 0.94\ Q_{T,COV} \tag{8}$$

By analogy with the mid-range temperature results, one would also expect little difference in radiation amounts measured at different locations on the valley floor, at least when dealing with accumulated values of total daily radiation (i.e., k_4, Eq. (5)). Fig. 5 shows a test of this hypothesis. The average percentage difference is as high as ~11% (e.g., the variety 1604/early planting sample) and the standard deviation can be as large as ~10%. These are unexpected results, and this subject should be explored further, especially if pheno-climatological models using solar radiation are to be used.

V. MODELING RESULTS

All of the models for plant growth, Eqs. 1-7, require the statistical estimation of their parameters using suitable phenological and climatological data spread over a period of several years. For example, the basis a_1 for the heat-unit model, Eq. (2), is found by the method illustrated in Fig. 6. For each basis a_1, the coefficient of variation of k_1 is computed. The appropriate basis for any set of data is then the value of a_1 that minimizes the coefficient of variation of k_1 (i.e., that makes the constant k_1 most "constant"). This technique has been used by other authors (e.g., Caprio, 1971). Unfortunately, in this study, the method worked only with the Salem area data for Asgrow 290 [~46°F (7.8°C) and ~54°F (12.2°C) for the middle and late plantings respectively]. To avoid this difficulty, the models were then run for one or two different bases (45°F and 50°F or 7.2°C and 10°C). These are the values which have been customarily used as bases for snap beans in the Willamette Valley.

All of these various models are based on the summations of variables or combinations of variables from a planting date P to a maturity date M. In this study, the date of maturity is approximated by the date of harvest and the associated percentage of the crop in Grades 1 and 2. Only for the statistical models, Eq. (7), are any grade information included.

Table 5 shows the mean and standard deviation of the accumulated values of each model tested on these snap-bean samples (i.e., the mean and standard deviation of $k_o,\ldots,k_6$). In previous studies of this type, the mean value has always been used as the estimator of the k of the model being studied. Since these k's are supposed to be constants, the coefficient of variation (the standard deviation dividied by the mean) is used as a measure of how well the model performs.

Table 6 shows the coefficient of variation of each k for each model for each snap-bean sample. Although these results do not permit the unambiguous identification of a "best" model, the following should be noted:

a. The statistical models (Eq. (7)) look promising when the correlation between grade and day-to-harvest is significant.

Table 6. The coefficient of variation of snap bean samples (Table 1) and for each model to be tested. The models are ranked in increasing order of the coefficient of variation.

		Variety/Planting Season							
		1604/Early		1604/Middle		290/Middle		290/Late	
Area	Model	Coefficient	Ranking	Coefficient	Ranking	Coefficient	Ranking	Coefficient	Ranking
Salem	Réaumur	0.04023	3	0.03019	1	0.04638	9	0.02818	10
	Bates	0.04322	4	0.03117	2	0.05303	11	0.03034	11
	Nuttonson (45°F)	0.05566	5	0.03638	3	0.03500	3	0.02366	6
	Nuttonson (50°F)	0.05727	7	0.03701	4	0.03474	2	0.02332	5
	Heat Unit (45°F)	0.05642	6	0.03804	6	0.03562	4	0.02530	8
	Heat Unit (50°F)	0.06740	10	0.04217	9	0.03645	5	0.02456	7
	Caprio (45°F)	0.06733	9	0.04149	8	0.04006	6	0.02184	2
	Caprio (50°F)	0.07837	11	0.04506	10	0.04014	7	0.02030	1
	Rad-Temperature	0.06575	8	0.03896	7	0.04315	8	0.02234	3
	Statistical (none)	0.01196	1	0.09663	11	0.02975	1	0.02297	4
	Statistical (45°F)	0.02117	2	0.03801	5	0.04996	10	0.02714	9
Eugene	Réaumur	0.05260	1			0.06134	2	0.07121	1
	Bates	0.05328	2			0.06252	3	0.07133	2
	Nuttonson (45°F)	0.07110	3			0.08025	5	0.08303	4
	Nuttonson (50°F)	0.07272	4			0.08322	6	0.08484	5
	Heat Unit (45°F)	0.07279	5			0.08590	7	0.08960	6
	Heat Unit (50°F)	0.08447	8			0.10501	9	0.10072	9
	Caprio (45°F)	0.08575	9			0.10682	10	0.09687	8
	Caprio (50°F)	0.09767	11			0.02574	11	0.10610	10
	Rad-Temperature	0.07873	7			0.09501	8	0.09518	7
	Statistical (none)	0.07497	6			0.06571	4	0.11437*	11
	Statistical (45°F)		10			0.03570	1	0.07867*	3

*Only 26 of these had grade information

b. The radiation-temperature model (Eq. (6)) usually out-performs the Caprio model (Eq. (4)), but it would need to be fit to the data to be optimized.

c. Of the remaining models, the simpler ones seem to work better. This is true even of Bates' model (Eq. (5)) for which it was necessary to use only the Corvallis solar radiation data.

d. Caprio's model appears to be the worst, but it is not known how sensitive this model is to the use of the Corvallis Q_T values.

Figure 7 shows a comparison among all the older, established models. The surprising thing is how well Réaumur's model performs. It has not been used, at least to these authors' knowledge, since the heat-unit model gained wide-spread acceptance more than a century ago.

VI. RECOMMENDATIONS FOR FUTURE WORK

This study has laid the foundations for future research which may have a practical impact on Oregon agriculture. In the short term several things ought to be done.

a. More solar radiation data should be gathered (e.g., University of Oregon's 1978 data), especially data from the northern half of the valley. Then a more detailed analysis of the radiation climatology should be made which would include a study of the relationship between solar radiation and temperature (e.g., Ojo, 1973).

b. The climatological data base should be extended to include April data and data from Area 4.

c. The models should be tested in a way that expressed the results in terms of the root-mean-square error (RMSE) in days-to-harvest. A practical criterion for model selection is not a lower coefficient of variation of k, but rather whether or not it has a RMSE days-to-harvest smaller than others by at least one day.

d. The models should all be tested using either independent data or a "jack-knife" procedure to see how well they perform when trying to predict harvest dates using climatological data.

The initial application of the results of this paper is presented as Appendix B. This appendix shows the simplest way that climatological data can be used with these models and recommends further testing by interested agriculturists. If these models are to be used outside the Willamette Valley, new varietal constants should be determined, and the models should again be evaluated to see which one(s) work best in any particular area.

VII. SUMMARY AND CONLUSIONS

The preceeding sections have discussed the climatology, the phenoclimatological models and the snap-bean field records used in this study. This study has necessarily taken a rather broad-brush approach to studying the climatological aspects of the problem, and it has also been necessary to use only a small number of snap-bean records. However, for the first time, the results of several different climatological models have been compared.

Until more definitive results from further research become available, we recommend that either Réaumur's model (Eq. (1b)) using the summation of mid-range temperatures from the nearest climate station or Bates' model (Eq. (5)) using the summation of Corvallis total daily solar radiation amounts be used by the snap-bean processors in this valley and that the results of these models be compared with the old heat-unit, base 45°F model (Eq.(2b)).

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IX. ACKNOWLEDGEMENTS

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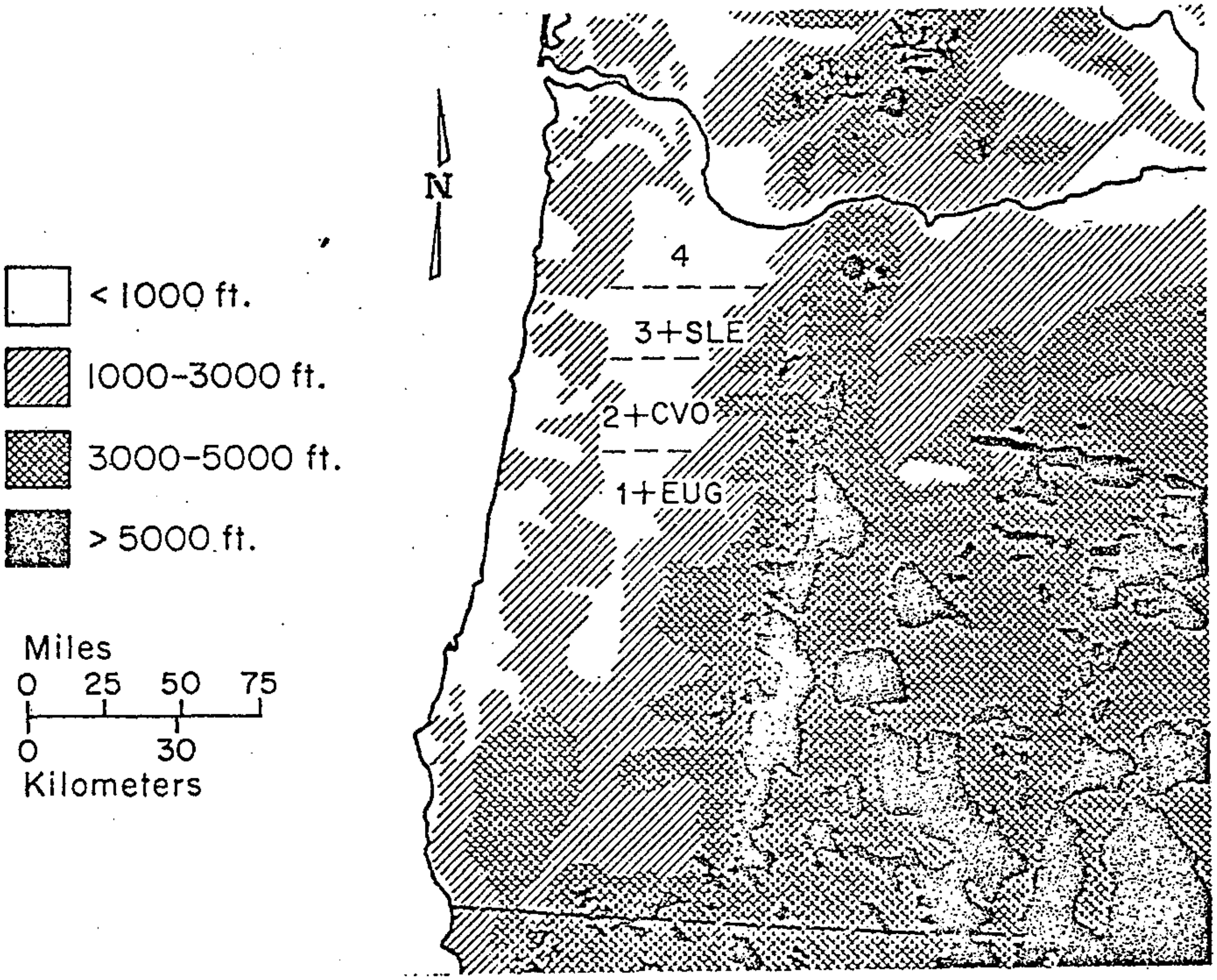


Fig. 1. Topographic map of western Oregon showing the location of the four areas within the Willamette Valley used in this study (set off by dashed lines) and the locations (+) of the airports at Eugene (EUG), Corvallis (CVO) and Salem (SLE). (Adapted from a base map, courtesy of R. W. Baker.)

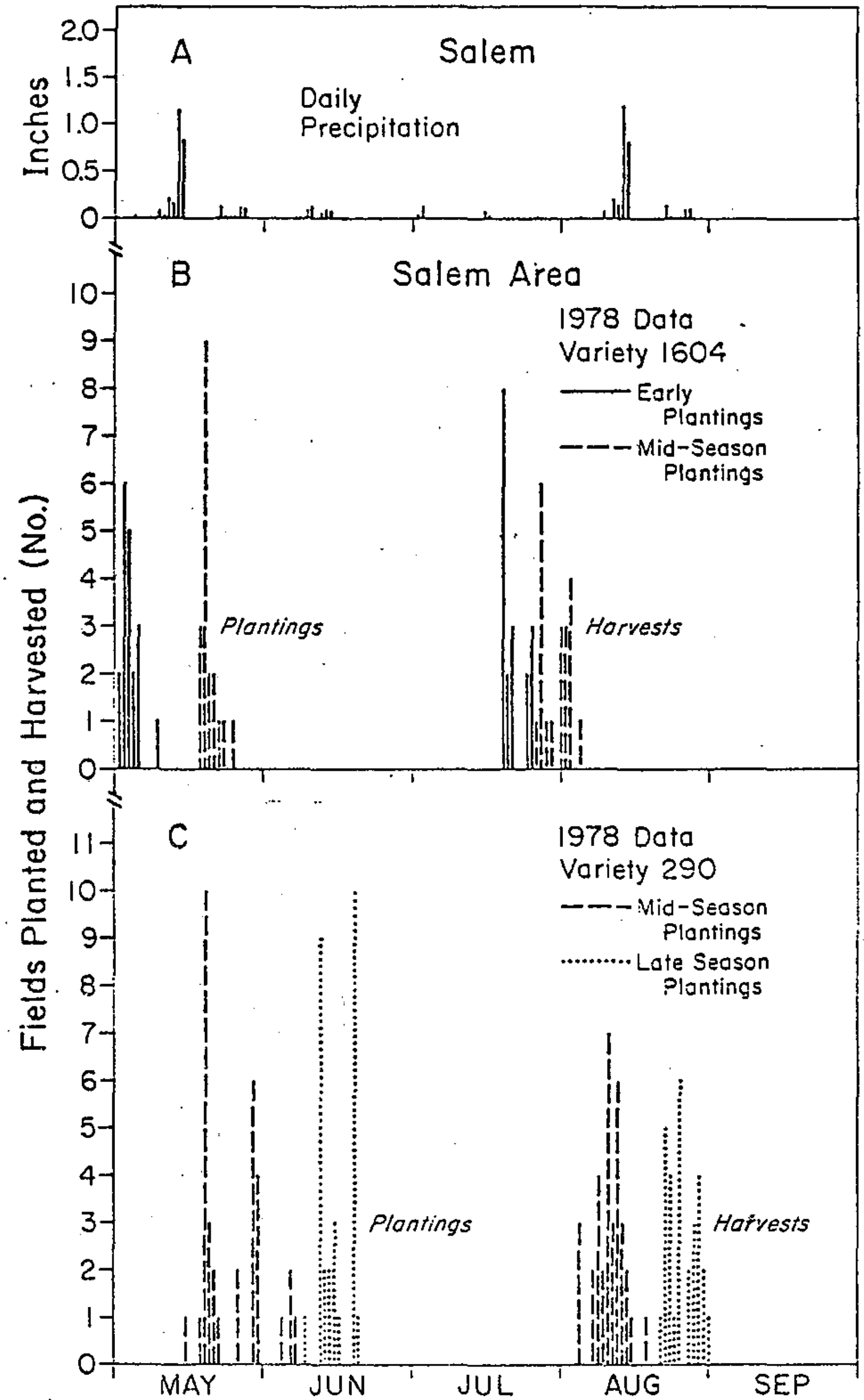


Fig. 2. Daily precipitation amounts recorded at the Salem airport (SLE) for May thru August 1978 (Section A). Number of plantings and harvests by date for the Salem Area snap bean samples (Sections B & C).

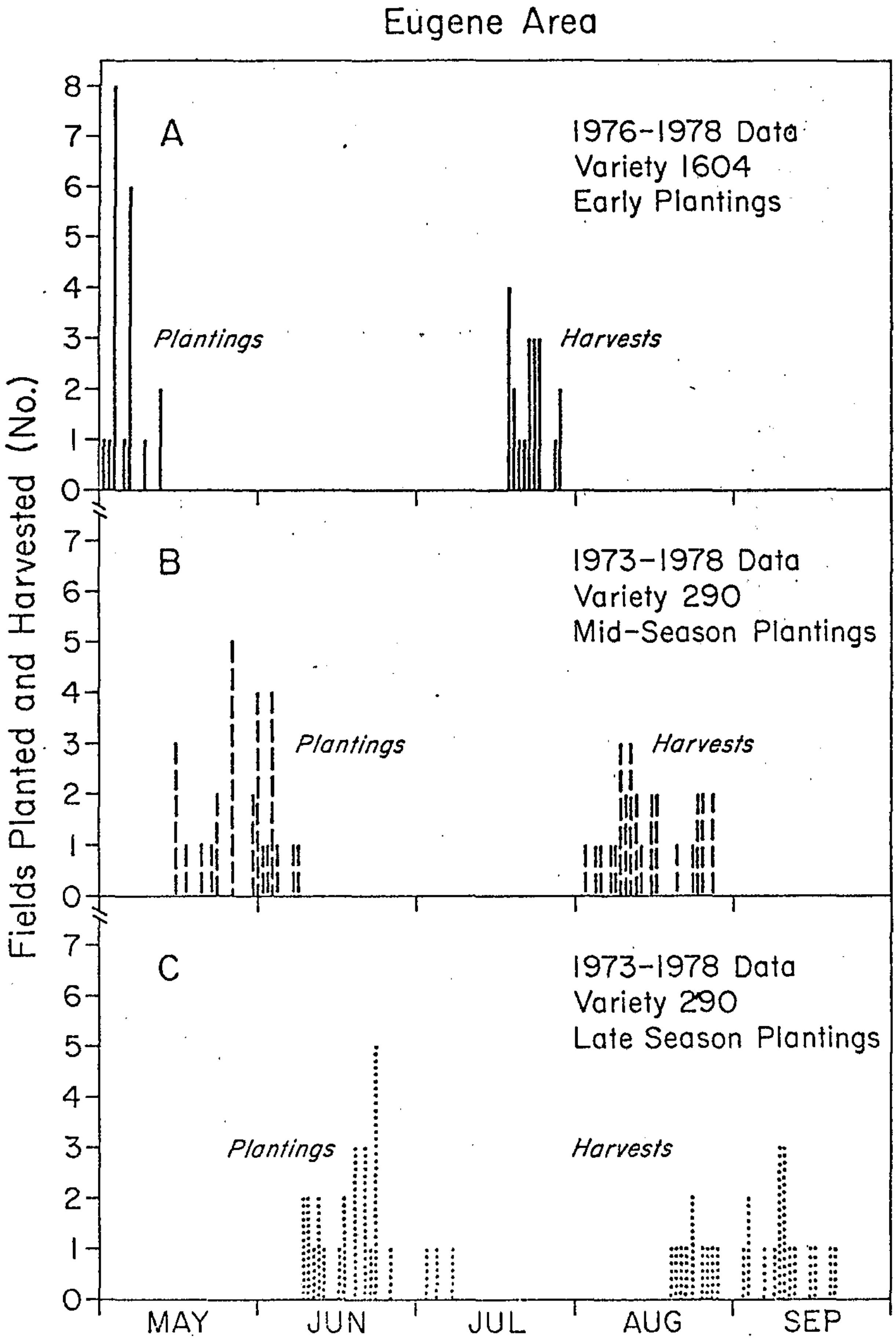


Fig. 3. Number of plantings and harvests by date for the Eugene area snap bean samples.

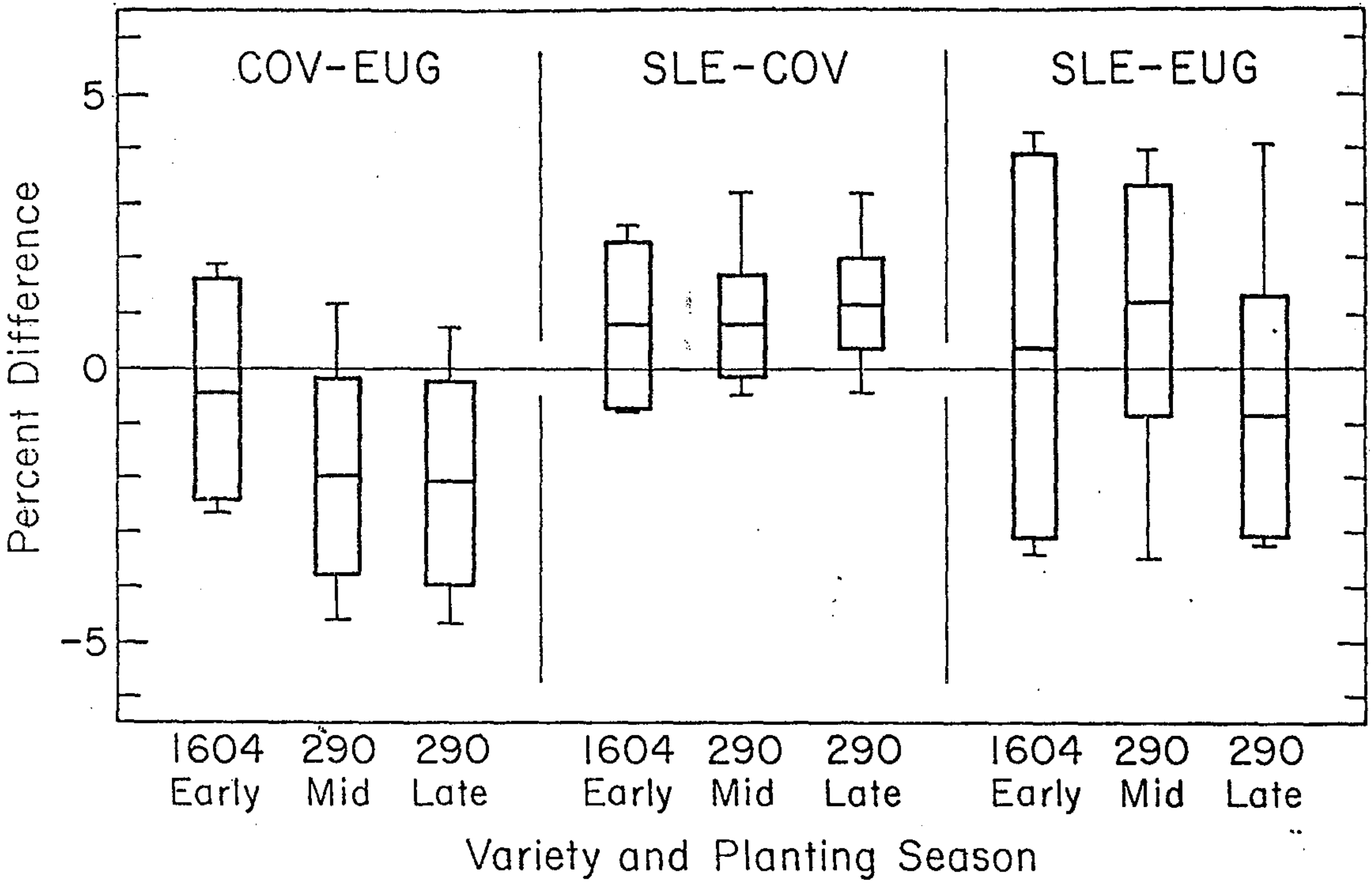


Fig. 4. Based on the planting and harvest dates for the samples from the Eugene Area, this box and whisker plot (see text for definition) is for the differences (defined as north minus south) among the accumulated mid-range temperatures at these sites (i.e., k_0, Eq. (1)) as a percentage of the mean Corvallis accumulated mid-range temperature.

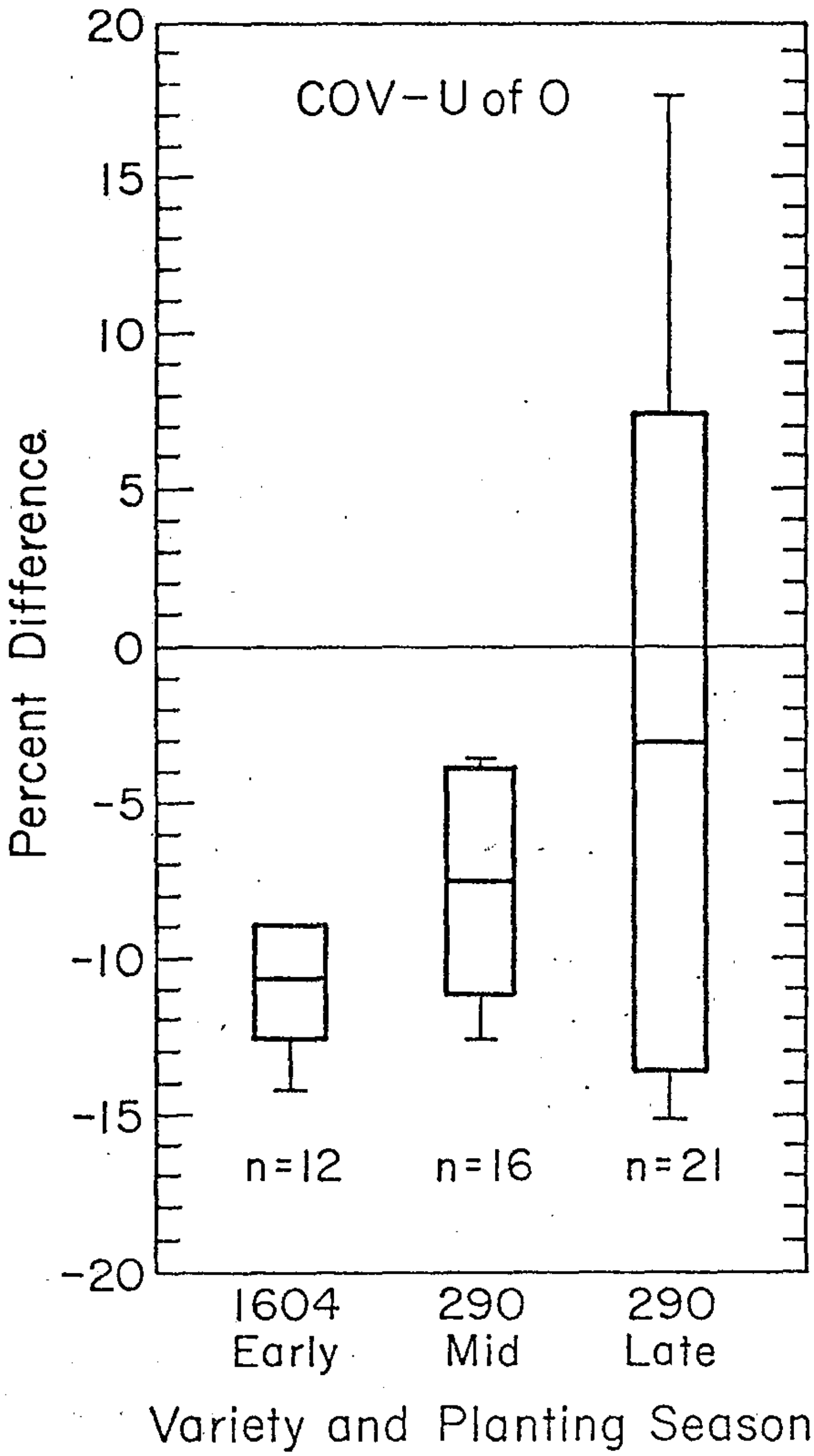


Fig. 5. Same as Fig. 4 except that the differences are in the accumulated total daily radiation values (i.e., k_4, Eq. (5)) between COV and the U of O radiation records. Note: The sample sizes are smaller because of the short U of O radiation record.

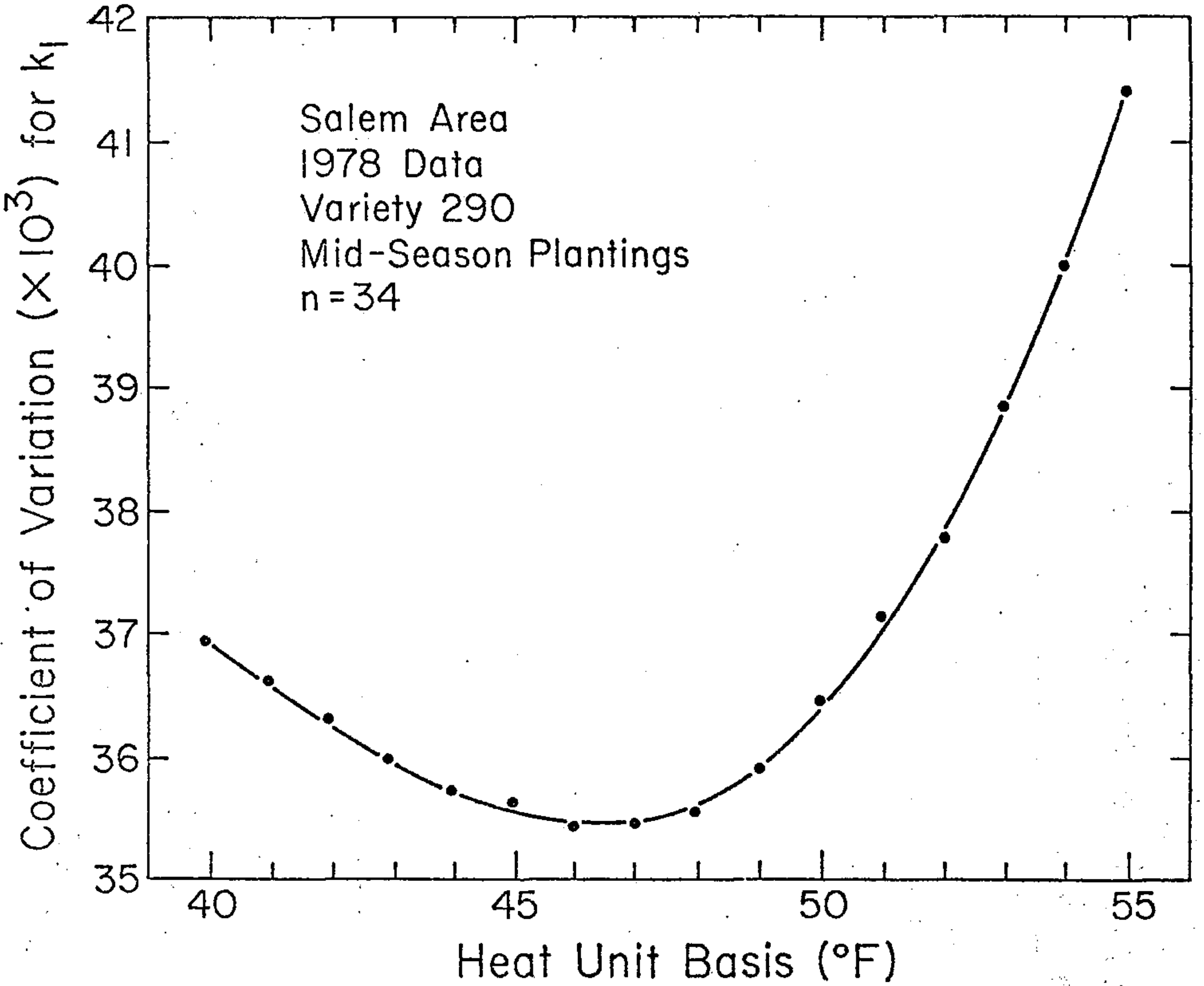


Fig. 6. The change in the coefficient of variation for the heat unit model summation as a function of the basis used in the model.

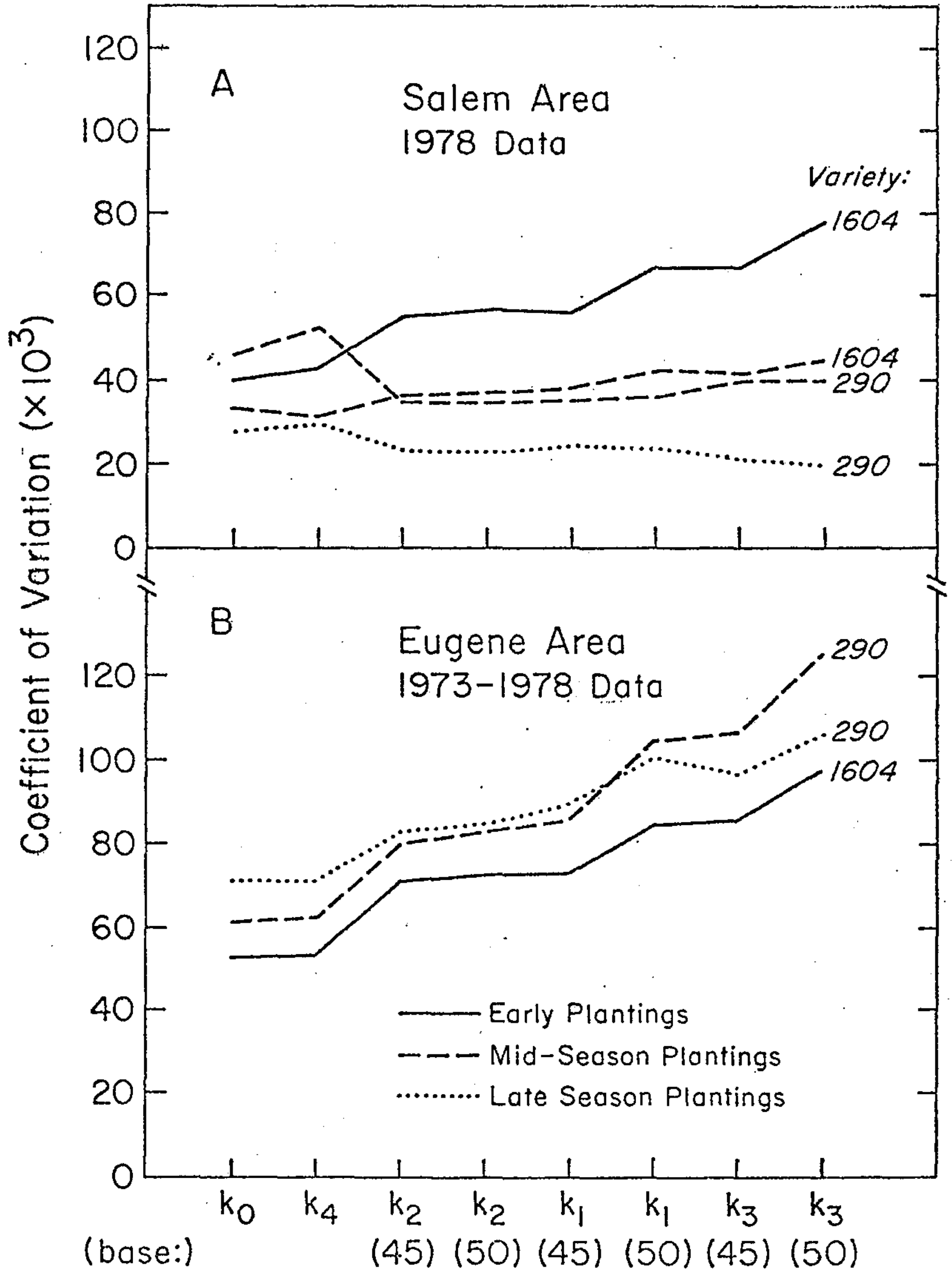


Fig. 7. The coefficient of variation for the K-constant of four established pheno-climatological models (k_0, Réaumur; k_1, heat unit; k_2, Nuttonson; k_4, Bates) based on each snap bean sample (Table 1). The bases are in degrees Farenheit.

APPENDIX A

In this study, the limited number of available variables are: the number of days to maturity (M to P), the daily averaged temperature T_m as approximated by the daily mid-range temperature, the total amount of daily global radiation Q_T, and the day length L. It is possible to derive Eq. (7a) starting with an equation for leaf temperature T_L (Linacre, 1964) which has been modified to leave out the effects of latent heat:

$$T_L = T + (r/\rho c_p)Q^* \tag{A-1}$$

where:

T is the ambient temperature
ρ is the density of the air
Q^* is the net radiation
c_p is the specific heat at constant pressure
r is the resistance.

According to Bay (1971), there is always a significant linear relationship between net radiation Q^* and the downwards flux of solar radiation $K\downarrow$, i.e.,

$$Q^* = \gamma_0 + \gamma_1 \quad K\downarrow \tag{A-2}$$

Combining Eqs. A-1 and A-2, ignoring any contribution of the nighttime net radiation on a daily average leaf temperature and then crudely taking a daily average, we have:

$$\overline{T}_L \approx T_m + \left(\frac{r\gamma_0}{\rho Cp}\right) + \left(\frac{r\gamma_1}{\rho Cp}\right) Q_T/L \tag{A-3}$$

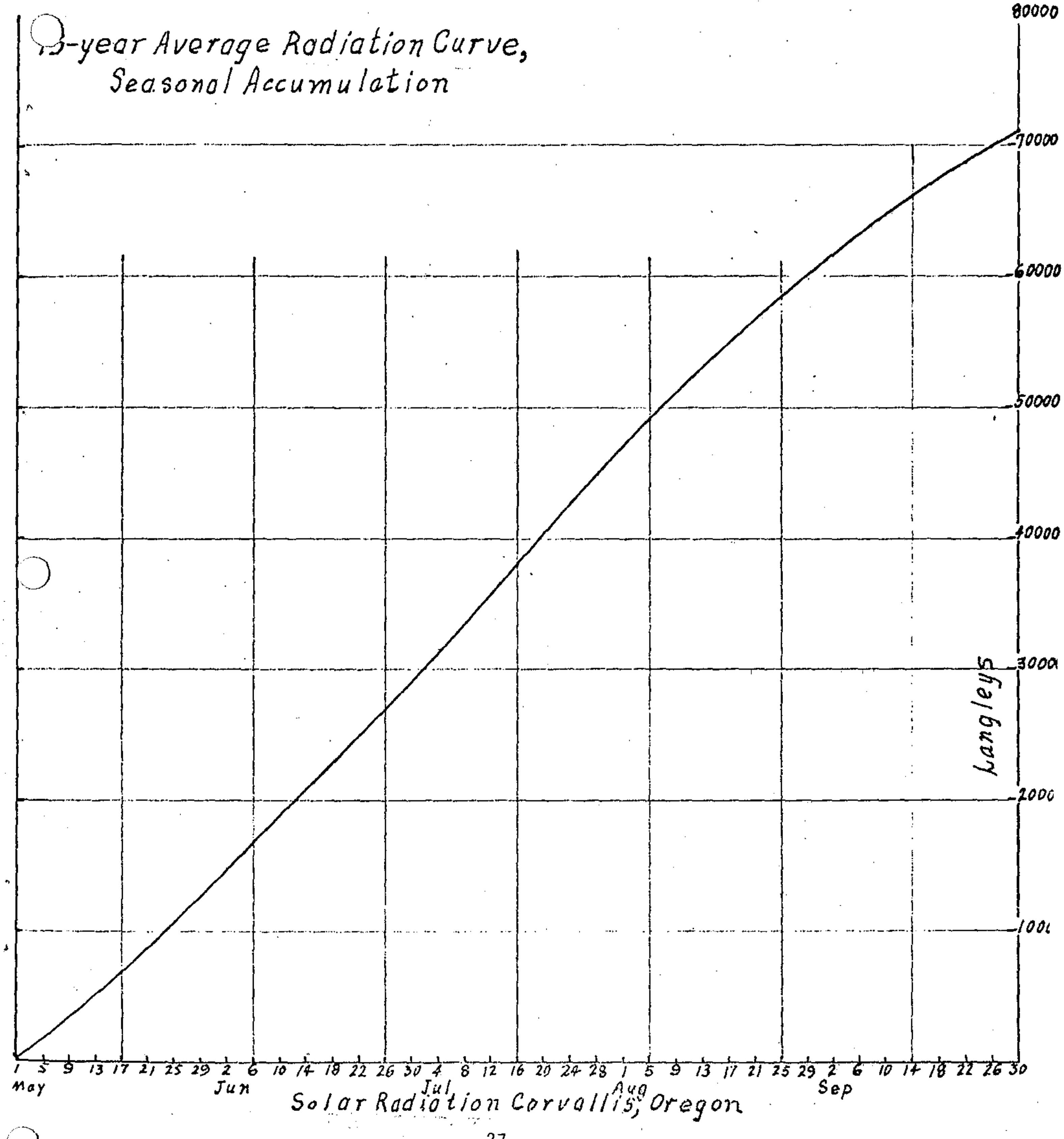
This suggests the following model for plant development:

$$\sum_{P}^{M} \overline{T}_L = k_6 \tag{A-4}$$

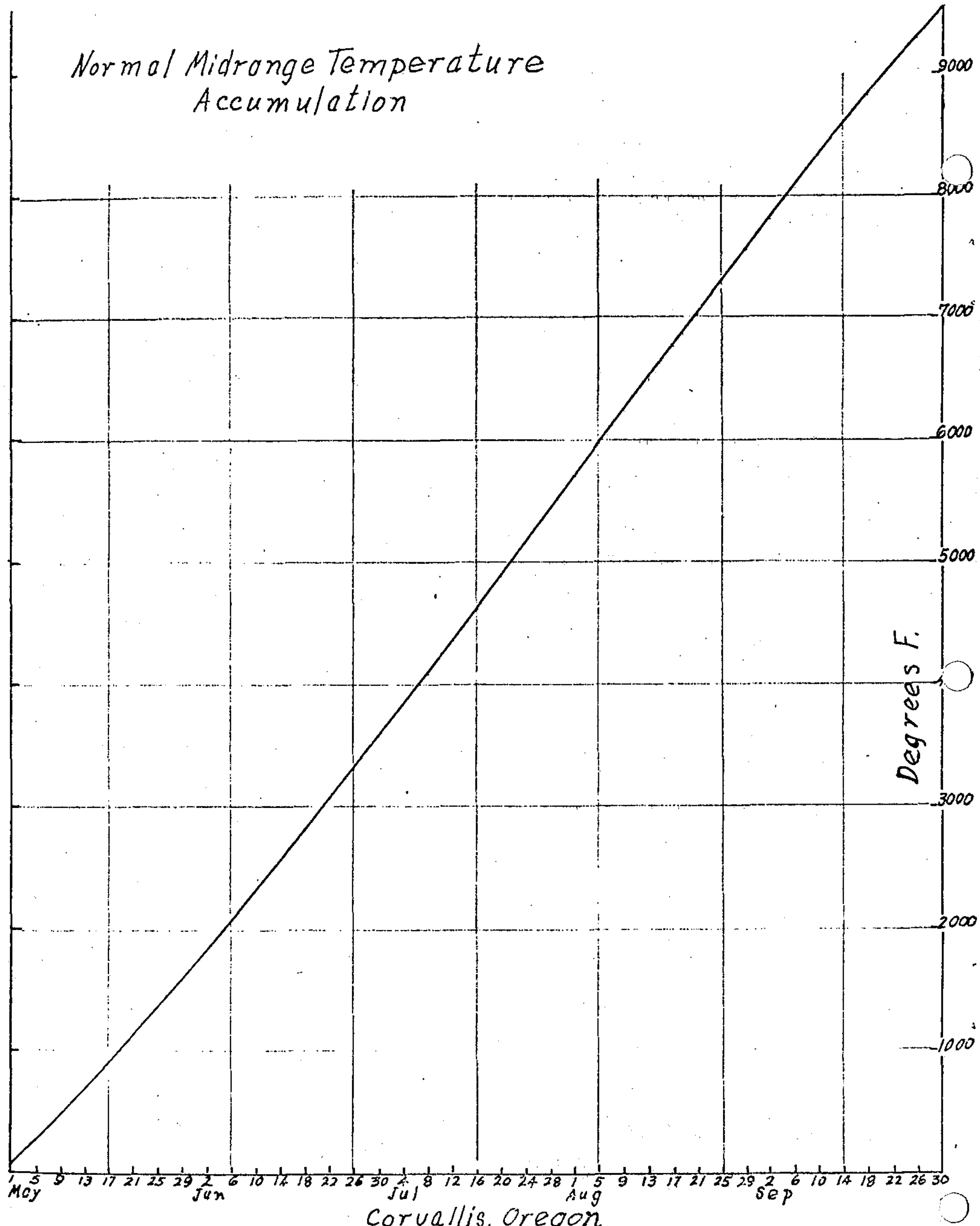
where k_6 might be called the number of leaf degree days.

APPENDIX B

An application of the models is shown here. The accompanying graphs show the accumulation of temperature in degrees F. and radiation in langleys from May 1 to September 30 for Corvallis, Oregon. To use either graph, one selects the appropriate "constant" for variety and planting period. The expected maturity date can be found by entering the curve with the date of planting and following up the curve with the number of units of the "constant".



15-year Average Radiation Curve,
Seasonal Accumulation
80000
70000
60000
50000
40000
3000
2000
1000
Langleys
1 5 9 13 17 21 25 29 2 6 10 14 18 22 26 30 4 8 12 16 20 24 28 1 5 9 13 17 21 25 29 2 6 10 14 18 22 26 30
May
Jun
Jul
Aug
Sep
Solar Radiation Corvallis, Oregon



Normal Midrange Temperature Accumulation
9000
8000
7000
6000
5000
3000
2000
1000
Degrees F.
1 5 9 13 17 21 25 29 2 6 10 14 18 22 26 30 4 8 12 16 20 24 28 1 5 9 13 17 21 25 29 2 6 10 14 18 22 26 30
May
Jun
Jul
Aug
Sep
Corvallis, Oregon

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