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Deriving a Biophotothermal Time Scale for Barley*

by

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INTRODUCTION

A number of authors have used temperature, together with one or more other elements, to estimate how quickly crops could be expected to develop and whether they would be likely to reach maturity under a given set of meteorological conditions. Unstead (1912) used temperature and photoperiod in estimating the northern limits for potential wheat production in North America, and he allowed for the non-linearity of temperature effects. Primault (1969) used temperature, sunshine duration, and precipitation to obtain indices to map the limits for maize production in Switzerland.

A major cooperative crop-weather experiment was conducted from 1953 to 1962 at nine locations in Canada. For many crop-weather study purposes in Canada, the comprehensive set of data obtained in this experiment is still the best available material, and analysis of it is continuing.

Robertson (1968) reviewed the work of various other authors and then presented a biometeorological time scale derived from his analysis of the data for wheat TRITICUM AESTIVUM, L. cult. Marquis) obtained in the Canadian crop-weather experiment. The computation of such a time scale involves the accumulation of meteorological events such as temperatures of various magnitudes. The accumulation required to bring a crop from one phenological stage to the next is estimated.

Following the example set for wheat by Robertson (1968), the present author analysed the data for barley in relation to daily temperature and photoperiod and reported the results in an unpublished thesis (Williams, 1971). Although Robertson used the term "biometeorological" in his analysis of the same meteorological variables, the present author has preferred to use "biophotothermal", to emphasize the fact that the only meteorological variables considered were temperature and photoperiod.

The present paper reviews the derivation of the biophotothermal time scale equations for barley. The applicability of the equations, and some other aspects of the analyses, will be examined in a subsequent paper.

DATA AND METHODS

The term "stage" will be used here to indicate a particular point in biological development or time. "Phase" will indicate the period from one specified stage to the next.

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Fig. 1. Map of Canada showing locations of stations which participated in the crop-weather experiment.

The meteorological data and the phenological stage definitions were the same as in the analysis for wheat (Robertson, 1968). Data had been recorded for an early maturing cultivar, Olli, of barley (HORDEUM VULGARE L. emend. Lam.) at nine locations in Canada (Fig. 1) for part or all of the 1953 to 1957 period, and in some instances several plantings were made at a location in one year. From the various locations, years and plantings, 56 separate cases were available for the analysis (Table 1).

TABLE 1. Olli barley phenological data from Canadian crop-weather experiment

Station	Yr.	No.	Date of reaching indicated phenological stage					
			P	E	J	H	S	R
Ottawa,	53	1	8 May	15 May	1 Jun	22 Jun	3 Jul	15 Jul
Ontario		2	26 May	4 Jun	17 Jun	7 Jul	19 Jul	29 Jul
45°24'N		3	10 Jun	16 Jun	29 Jun	17 Jul	27 Jul	5 Aug
75°43'W		4	24 Jun	30 Jun	15 Jul	12 Aug	17 Aug	28 Aug
79 m		5	9 Jul	16 Jul	31 Jul	16 Sep	------	30 Sep
		6	22 Jul	29 Jul	11 Aug	20 Sep	24 Sep	7 Oct
		7	6 Aug	14 Aug	28 Aug	30 Sep	------	------
	54	1	20 May	26 May	13 Jun	1 Jul	21 Jul	30 Jul
		2	8 Jun	13 Jun	22 Jun	14 Jul	30 Jul	2 Aug
		3	18 Jun	22 Jun	1 Jul	27 Jul	13 Sep	23 Sep
		4	21 Jul	25 Jul	6 Aug	14 Sep	------	------
	55	1	5 May	11 May	28 May	16 Jun	30 Jun	14 Jul
		2	27 May	31 May	15 Jun	4 Jul	17 Jul	22 Jul
		3	23 Jun	29 Jun	16 Jul	9 Aug	------	------
		4	20 Jul	30 Jul	13 Aug	20 Sep	------	------
	56	1	8 Jun	12 Jun	28 Jun	19 Jul	7 Aug	17 Aug
		2	4 Jul	8 Jul	20 Jul	16 Aug	7 Sep	21 Sep
		3	1 Aug	6 Aug	21 Aug	------	------	------
	57		7 May	13 May	30 May	19 Jun	3 Jul	18 Jul
Normandin,	53		25 May	1 Jun	------	8 Jul	20 Jul	24 Aug
Quebec	54		15 Jun	21 Jun	------	25 Jul	18 Aug	27 Aug
48°51'N	55		27 May	5 Jun	23 Jun	9 Jul	1 Aug	19 Aug
72°32'W	56		29 May	4 Jun	19 Jun	9 Jul	18 Aug	4 Sep
137 m	57		21 May	31 May	22 Jun	11 Jul	2 Aug	16 Aug
Harrow,	53		13 May	19 May	9 Jun	20 Jun	7 Jul	14 Jul
Ontario	54		21 Apr	26 Apr	------	4 Jun	16 Jun	28 Jun
42°02'N	55		2 Apr	10 Apr	28 Apr	24 May	7 Jun	21 Jun
82°54'W	56		9 Apr	23 Apr	17 May	10 Jun	20 Jun	4 Jul
191 m								
Kapuskasing	53	1	25 May	5 Jun	15 Jun	9 Jul	------	17 Aug
Ontario		2	1 Jun	11 Jun	23 Jun	16 Jul	------	21 Aug
49°25'N		3	8 Jun	15 Jun	26 Jun	20 Jul	------	24 Aug
82°26'W								
218 m								
Swift Current	53		16 May	29 May	------	10 Jul	24 Jul	3 Aug
Sask.	54		19 May	28 May	------	7 Jul	------	13 Aug
50°16'N	55		19 May	26 May	10 Jun	4 Jul	1 Aug	11 Aug
107°44'W	56		17 May	22 May	6 Jun	30 Jun	24 Jul	30 Jul
825 m	57		8 May	17 May	5 Jun	28 Jun	15 Jul	22 Jul
Lacombe,	53		14 May	3 Jun	19 Jun	12 Jul	------	------
Alberta	54		21 May	30 May	23 Jun	8 Jul	10 Aug	20 Aug
52°28'N	55		11 May	19 May	8 Jun	1 Jul	19 Jul	31 Jul
113°45'W	56		18 May	25 May	18 Jun	6 Jul	31 Jul	10 Aug
848 m	57		16 May	21 May	6 Jun	2 Jul	24 Jul	12 Aug

TABLE 1. Continued

Station	Yr.	No.	P	E	J	H	S	R
			Date of reaching indicated phenological stage					
Beaverlodge,	53		21 May	30 May	16 Jun	11 Jul	29 Jul	13 Aug
Alberta	54		17 May	25 May	12 Jun	3 Jul	23 Jul	6 Aug
55°11'N	55		4 May	18 May	7 Jun	26 Jun	15 Jul	27 Jul
119°22'W	56		11 May	20 May	10 Jun	4 Jul	22 Jul	3 Aug
762 m	57		6 May	17 May	6 Jun	4 Jul	29 Jul	14 Aug
Fort	53		23 May	28 May	12 Jun	2 Jul	20 Jul	26 Jul
Vermilion,	54		28 May	11 Jun	24 Jun	13 Jul	------	17 Aug
Alberta	55		17 May	25 May	2 Jun	27 Jun	10 Jul	18 Jul
58°23'N	56		18 May	25 May	5 Jun	26 Jun	22 Jul	10 Aug
116°03'W	57		16 May	24 May	10 Jun	29 Jun	4 Aug	19 Aug
279 m								
Fort	53		15 May	25 May	13 Jun	3 Jul	18 Jul	26 Jul
Simpson,	54		23 May	29 May	8 Jun	28 Jun	15 Jul	20 Jul
N.W.T.	55		18 May	27 May	8 Jun	28 Jun	7 Jul	12 Jul
61°52'N	56		7 May	23 May	1 Jun	27 Jun	12 Jul	19 Jul
121°21'W	57		8 Jun	14 Jun	26 Jun	15 Jul	29 Jul	7 Aug
131 m								

The following model was used:

$$1 = \sum_{i=S_1}^{S_2} \left[\{a_1(L_i-a_o) + a_2(L_i-a_o)^2\}\{ b_1(T_{1i}-b_p-b_n)+b_2(T_{1i}-b_p-b_n)^2 + b_3(T_{2i}-b_p-b_n) + b_4(T_{2i}-b_p-b_n)^2 \}\right] \quad (1)$$

where L_i = photoperiod (duration of daylight) on day i,
T_{1i} = maximum temperature on day i,
T_{2i} = minimum temperature on day i,
S_1 = the date of some stage in the development of barley toward maturity,
S_2 = the date of the next stage,
a_1, a_2 and b_1 to b_4 are coefficients derived in the analysis,
a_o is the lower critical limit or threshold value for photoperiod and
(b_p+b_n) is that for temperature. At any stage or iteration in the derivation procedure, b_p is the temperature threshold assumed or obtained previously and b_n is a new part to be derived, as will be explained later. This division of the temperature threshold into two parts, which is essential for the analyses, was not shown in the equations presented by Robertson (1968). The necessary equations have therefore been amended as required and included in the present paper.

The following phenological phases were considered: planting to emergence (P-E), emergence to jointing (E-J), jointing to heading (J-H), heading to soft dough (H-S), and soft dough to hard dough or ripe (S-R). A different set of limits and coefficients was derived for each phase.

If S_1, the date of one particular stage, is known, one can then use equation (1) with the appropriate set of coefficients to estimate the date of S_2, the next stage, from the meteorological data, by summing the products indicated in the equation for as many consecutive days as are necessary to make the sum equal to 1. If only the planting date and the meteorological data are given, one can continue the summation through all five phases, using the P-E parameters until the sum reaches 1, the E-J ones until it reaches 2, and so on, until the dates have been estimated for all stages. Between stages decimals are used, for example a biophotothermal time of 2.5 indicates half way from jointing to heading.

Algebraic manipulations were performed with Eq. (1) to obtain equations suitable for use with iterative procedures involving regression analysis with linear coefficients. If we let

$V_{1i} = \{a_1(L_i-a_o) + a_2(L_i-a_o)^2\}$, the following can be derived from Eq. (1):

$$\frac{1}{\Sigma V_{1i}} = p_o+p_1\frac{\Sigma V_{1i}(T_{1i}-b_p)}{\Sigma V_{1i}} + b_2\frac{\Sigma V_{1i}(T_{1i}-b_p)^2}{\Sigma V_{1i}} +$$

$$p_3\frac{\Sigma V_{1i}(T_{2i}-b_p)}{\Sigma V_{1i}} + b_4\frac{\Sigma V_{1i}(T_{2i}-b_p)^2}{\Sigma V_{1i}} \qquad (2)$$

Equation (2) can be used in regression analysis to derive its coefficients. The b_2 and b_4 values are as required for Eq. (1). The other parameters for the temperature terms in Eq. (1) can then be obtained as follows:

$$b_n = \frac{-(p_1+p_3) \pm \sqrt{(p_1+p_3)^2-4(b_2+b_4)\,p_o}}{2(b_2+b_4)},$$

$b_1 = p_1+2b_2b_n$, and $b_3 = p_3+2b_4b_n$.

To obtain the threshold temperature, (b_p+b_n), for use in the biophotothermal time scale, a pre-assigned value, b_p, is adjusted by adding the new part, b_n.

Similarly, if we let $V_{2i} = b_1(T_{1i}-b_p-b_n)+b_2(T_{1i}-b_p-b_n)^2$ and $V_{3i} = b_3(T_{2i}-b_p-b_n) + b_4(T_{2i}-b_p-b_n)^2$, Eq. (1) can be transformed to:

$$\frac{1}{\Sigma(V_{2i}+V_{3i})} = q_o+q_1\frac{\Sigma (V_{2i}+V_{3i})L_i}{\Sigma (V_{2i}+V_{3i})} + a_2\frac{\Sigma (V_{2i}+V_{3i})L_i^2}{\Sigma (V_{2i}+V_{3i})} \qquad (3)$$

The coefficients for Eq. (3) can be derived by regression analysis. The resulting a_2 value is as required for Eq. (1). The other parameters needed for the photoperiod terms in Eq. (1) can be computed as follows:

$$a_o = \frac{-q_1 \pm \sqrt{(q_1^2-4a_2q_o)}}{2a_2},$$

$a_1 = q_1+2a_2a_o$.

The equations were applied to the data for each phenological phase, using iterative procedures which usually proceeded as follows:

Step 1: Assign initial values of the a's and b's
Step 2: Compute the V_1 values for the phase, and derive a value for b_n and new values for b_1, b_2, b_3 and b_4 using regression analysis performed with Eq. (2).

Step 3: Compute the V_2 and V_3 values, and derive new a_o, a_1 and a_2 parameters using regression analysis performed with Eq. (3).

Step 4: Revise b_p by adding b_n to the previous value of b_p, and repeat Step 2, using the latest a_o, a_1 and a_2 values.

Steps 3 and 4 were performed repeatedly. Also, after each iteration of a step, the sum, k, of the right hand side of Eq. (1), was computed for each of the 56 cases. Usually as iteration proceeded a point was reached when the average of k for these cases stabilized at some value close to 1, the coefficient of variation of k stopped decreasing, and the computed parameters no longer changed appreciably from one iteration to the next. At this point a final set of a's and b's was selected.

The choice of initial values to be used in Step 1 is not usually critical, except that they should not ordinarily be such as to cause elimination of any of the data at the start.

Where the value computed for a bracketted term turns out to be negative, it is rejected. For example, if L_i is less than a_o, $(L-a_o)$ is set to zero for day i. In that case the whole contribution to the summation would be 0 for day i. In preparing data for Eq. (2), if the maximum temperature T_{1i}, was less than b_p, the data for day i would in effect be rejected, since the minimum would also be less than b_p and the four terms involving T_1 or T_2 would therefore be set to zero, so the daily product would be zero and nothing would be added to the accumulation of the sum for day i.

If T_{1i} is higher but T_{2i} is lower than b_p, the (T_2-b_p) terms are set to zero for day i for Eq. (2). This in effect eliminates the contribution of minimum temperature on day i, making that contribution the same as it would be on a day when $T_2 = b_p$. The corresponding equation in the wheat study (Robertson, 1968) was presented in a way that implied that T_2 rather than T_2-b_p would be set to zero in such a case. This was not actually done; if it had been the program would, in effect, have tried to fit a curve to minimum temperatures that included zeroes for such days, and the derived threshold would tend to be so low that too few minimum temperatures would be rejected in the next iteration. The number of cases rejected for T_2 would be alternately large and small with subsequent applications of Eq. (2) and stability would not be achieved. This would be particularly serious for computations in the Fahrenheit scale, since 0^oF would probably be much farther from the threshold value than 0^oC.

For computational purposes a_o was considered to be composed of two parts, just as the temperature threshold was. This was not essential, however, since the problem associated with setting a term to zero in the case of minimum temperature did not arise with photoperiod, so for simplicity, a_o is shown here as a single variable.

If, after using Eq. (2), the term under the square root sign is found to be negative, the regression analysis is repeated with the equation obtained by omitting the b_2 and b_4 terms. In that case, $b_n = -p_o/(p_1+p_3)$, $b_1 = p_1$ and $b_3 = p_3$. If the term under the root sign is negative after using Eq. (3), the analysis is repeated without the a_2 term, and $a_o = -q_o/q_1$ and $a_1 = q_1$.

In many applications of biophotothermal time scale equations, the only given date would be the planting date. In computations for the E-J phase, for example, one would often have the emergence date as estimated from the P-E computations, but not the actual emergence date. Robertson (1968) suggested that the regression analysis for the E-J phase should use the estimated emergence dates, to avoid errors that might otherwise arise in using the equation due to the fact that the starting date of the phase was selected differently in the application than in the regression analysis. Also, in some instances the dates reported for a stage that was difficult to observe seemed less reliable that the estimated dates. In view of these considerations Robertson (1968) used estimated starting dates in his regression analyses for the E-J and later phases.

It has been shown (Williams, 1971), however, that when estimated rather than actual values of S_1 are used in such analyses, the resulting equations are likely to give less accurate estimates, especially when the duration of a phase is of particular interest. The observed S_1 dates have therefore been used in deriving the parameters in the present study, except in a few cases where it was considered worthwhile to use estimates where the observed dates were missing.

It was assumed that photoperiod could be ignored for the period prior to emergence. For the P-E phase, therefore, the a's were set so that V_1 was effectively equal to unity for all values of L and the iterations were performed using Eq. (2) only.

RESULTS

When k, the sum of the right hand side of Eq. (1), was computed, using the derived equations, its average ranged from 1.03 to 1.15 for the various phases. This positive bias was found to be mostly attributable to the fact that in using Eq. (1) to estimate a stage date, S_2 was always taken as the date when k became equal to or greater than 1. If, instead, S_2 had been specified as the closest date to the time when the summation reached 1, so that, for example, S_2 would be taken as the date when k was equal to 0.95 rather than the following day when $k \approx 1.10$, this bias would have been practically eliminated.

It was also found that there was a negative bias, that is a bias toward earliness, in estimates of S_2 made using the derived parameters. This is not so easy to explain as the bias in k, but from the model one would not necessarily expect unbiased estimates of S_2. The sets of parameters tabulated here (Table 2) have been adjusted to remove the bias for S_2, usually by reducing the absolute value of a_1 slightly to make the estimated S_2 date slightly later.

TABLE 2. Parameters for equation (1) for estimating barley biophotothermal time from daily photoperiod (hours) and maximum and minimum temperature (^oC)

	Phenophase				
	P-E	E-J	J-H	H-S	S-R
Number of Cases Analyzed	56	51	55	42	42
Parameters:					
a_o	0.100×10^{20}	6.136	11.00	2.061	-0.6970
a_1	-0.989×10^{-19}	1.297	0.1841	0.3229	0.08793
a_2	0	0	-0.01334	0	0
b_o*	4.34	10.09	-1.361	15.91	4.144
b_1	0.01664	0.001128	0.004423	0.002927	0
b_2	-0.0005417	-0.00005725	-0.00008797	-0.0001638	0
b_3	0.01416	0.0007619	0.002052	0.02282	0.01687
b_4	-0.0004805	-0.00001854	-0.000009571	-0.004666	-0.0007821

*) $b_o = b_p + b_n$, where b_n is the adjustment obtained in the last iteration with Eq. (2) used in selecting the parameters.

The planting to emergence analyses, made using the 56 available cases (Table 1), converged fairly well on a final set of values after three or four iterations of Eq. (2). After the fourteenth iteration there were no further changes in the values computed. The parameters from that iteration were taken as final (Table 2), after a_1 had been multiplied by 0.989 to remove a -0.09 day bias in the S_2 estimates. About 40% of the daily observed minimum temperatures for the P-E phase were below the 4.34°C threshold (Table 2), but most of the observed maximums were between the derived upper and lower critical limits, so the tabulated parameters for the P-E phase were based on some 60% of the minimum temperature observations and most of the maximum temperature observations for that phase.

There were 51 cases (Table 1) for which both S_1 and S_2 were available for the emergence to jointing analyses. A minimum value of the coefficient of variation of k was obtained with the seventh analysis, i.e. the fourth application of Eq. (2). The parameters from this iteration were accepted as final for the E-J phase (Table 2), after a_1 had been changed from 1.4 to 1.297 to eliminate the -1.08 day bias in the S_2 estimates. This seventh analysis involved 40% of the daily minimum temperature observations and about 92% of the maximums, the rest having been rejected as outside the limits indicated by the preceding iterations. The majority of the minimums were below the derived 10.09°C threshold.

There were 55 cases available with observed heading dates, but only 50 of these had jointing date observations (Table 1). The equation that had been derived for the E-J period (Table 2) was used to estimate the jointing dates from the emergence dates and the temperature and photoperiod data, for the five cases in which the jointing dates were missing, to enable use to be made of the heading date data in the jointing to heading analyses for these cases. Analyses for the J-H phase were then performed employing all 55 cases. The first J-H analysis, using Eq. (2), indicated a concave downward curve for maximum temperature and a concave upward one for minimum, and by the fifth analysis, i.e. the third for temperature, the results were such that all minimum temperatures were rejected in all subsequent iterations.

Since the coefficient of variation was somewhat higher after the rejection of the minimum temperatures, a way was sought to obtain an improved set of parameters based on an analysis which retained these data. A second set of analyses was performed, using as initial values a_0 to a_2 and b_0 to b_2 from the seventeenth analysis, and b_3 and b_4 from the third analysis, of the first set. In the second set, although the minimum temperature was rejected again after a few iterations, the parameters obtained after one analysis each for temperature and photoperiod implied curves that were concave downward for both maximum and minimum temperature, and the coefficient of variation was lower than any obtained in the first set of analyses. These parameters from the second analysis of the second set were therefore selected for use for the jointing to heading period.

This procedure, in which the final parameter values were from a very early iteration in the second set of analyses and were therefore influenced by the initial values used at the beginning of that set, was employed here deliberately as it provided parameters that gave better estimates than would otherwise have been obtained. Ordinarily, unless the initial values were set so as to eliminate a variable from the start, they did not influence the final results. For example, when both the sets of analyses involved here were allowed to continue for about 20 iterations, the final regression coefficient values obtained were such that the estimates that would be obtained from applying them to data would be the same.

Of the observational cases available for the J-H analyses, two minimum temperatures that were below the threshold were the only observations rejected in the derivation of the parameters. The J-H phase was the only phase for which the derived parameters included a quadratic photoperiod term, i.e. $a_2 \neq 0$. The minimum temperature term, while quadratic in form, is practically linear, with a threshold temperature of -1.36°C and no meaningful optimum.

A bias toward earliness was found in estimates of S_2 made using the J-H parameters as derived above, and it required the adjustment of two coefficients, since all the terms were quadratic. It was found by trial and error that changing a_1 and a_2 from their original values of 0.2005 and -0.01454 to 0.1841 and -0.01334 respectively eliminated the bias. The final parameters for J-H included these adjusted photoperiod coefficients (Table 2).

For the heading to soft-dough (H-S) phase, 42 cases were analyzed. A minimum value of the coefficient of variation occurred at the tenth analysis. The resulting parameters gave estimates of the soft dough date which were biased toward earliness by about two thirds of a day. These parameters were selected to be used for the H-S phase (Table 2), after reducing a_1 to 0.3229 from its original value of 0.3436, thereby increasing the estimates of durations from heading to soft dough sufficiently to remove the bias.

A large proportion of the minimum temperature observations were below the H-S threshold value of 15.91°C. The iteration from which the parameters were selected was an analysis involving most of the daily maximum temperature observations among the 42 cases but only about 14% of the minimum temperatures.

For the soft-dough to hard-dough or ripe phase (S-R), the same 42 cases as for the H-S phase were used. The first analysis yielded parameters such that the maximum temperature term was eliminated from all subsequent iterations. The parameters selected for the S-R phase were those from the eleventh analysis, which involved most of the minimum temperature observations in the 42 cases analyzed. These parameters, before adjustment, gave estimates which were biased toward earliness by about 1.7 days. This was overcome by reducing the original a_1 value of 0.09707 to 0.08793, to increase the estimated length of time from soft dough to hard dough enough to remove the bias (Table 2).

For comparison, analyses were performed for S-R with initial values of b_3 and b_4 set to zero. The computer had been programmed to exclude minimum temperature from the model in every subsequent iteration after both b_3 and b_4 became equal to zero, so this procedure forced the use of maximum rather than minimum temperature. The resulting equation was less useful. The coefficient of variation was about 42%, as compared with 38% for the equation using minimum temperature (Table 3).

TABLE 3. Mean phase durations, and coefficients of variation of k, for Olli barley compared to Marquis wheat

	P-E	E-J	J-H	H-S	S-R
Phase duration (days)					
Olli barley	8	16	23	19	12
Marquis wheat	9	20	26	25	15
Coefficient of variation of k (%)					
Olli barley	30	20	17	26	38
Marquis wheat	30	21	19	21	43

The claim that the use of observed S_1 dates results in parameters that give more accurate estimates of S_1 to S_2 durations than when estimated S_1 dates are used in the analyses was tested for the E-J phase. When estimated S_1 dates were used, the smallest coefficients of variation found for k for this phase exceeded

25%. When the observed emergence dates were used, the coefficient of variation was reduced to around 20% (Table 3).

In spite of the differences between crops, and in the details of the analyses, the coefficients of variation found for Marquis wheat (Robertson, 1968) were fairly similar to those found for Olli barley (Table 3).

DISCUSSION

The coefficients a_1, a_2, b_1, b_2, b_3 and b_4, derived for Eq. (1), are not unique values, since V_1 can be altered and $(V_2 + V_3)$ changed in the opposite direction to compensate without affecting the product. Robertson (1968) proposed criteria for standardizing these coefficients. Other, equally logical, criteria might be used, however, that could change the apparent relationship between temperature and photoperiod effects (Williams, 1971). It does not seem, therefore, that one can adequately assess the relative contributions of the different variables using this model. Also it could be misleading to try to compare the individual parameters for one crop or phase to the corresponding ones for other crops or phases, even if the details of the procedures had been the same and the same method of standardization were used. In view of this, no attempt has been made to standarize the parameters in the present study.

Difficulties such as those experienced in the jointing to heading and soft dough to ripe analyses, in obtaining equations that included both maximum and minimum temperature, were no doubt at least partly due to the fact that the same threshold had to be used for both. This use of one threshold for both temperatures was considered necessary for mathematical reasons, as explained by Robertson (1968). Quite useful estimation equations have been obtained in spite of it, but it makes the model less realistic and detracts from its value as an aid in understanding the processes involved.

Approximations of average day temperatures and average night temperatures would be closer together than the maximum and minimum temperatures, and using such approximations might facilitate the analysis as their thresholds would, therefore, presumably be closer together so there might be less difficulty in using the same threshold for both than was the case with maximum and minimum temperatures. In future research, however, some more fundamental alternative to the use of maximum and minimum temperature as employed here should be considered.

In the case of the soft dough to ripe phase, even though maximum temperature was not included in the parameters (Table 2), its effect would be reflected to some extent since maximum and minimum daily temperatures are fairly well correlated. During the ripening phase photosynthesis, which takes place during daylight, is rather insignificant, so the need to include both the maximum, to represent day temperatures, and the minimum, representing night temperatures, would be reduced. Temperatures cold enough to inhibit biological processes would be more likely to occur at night, so it is perhaps to be expected that development in the S-R phase would be more closely related to the minimum than to the maximum. This could help to explain why the equation involving minimum temperature resulted in estimates of k with a lower coefficient of variation than did equations which used the maximum but not the minimum temperatures.

The use of the iterative procedure in the P-E phase was similar to its use by Bassett, Holmes and MacKay (1961), who employed it in determining degree-day threshold temperatures for equations to estimate flowering dates of woody plants. The use of the iterative procedure for deriving biophotothermal time scale parameters for the phases after emergence is considerably more complex, and this may have implications which further complicate the problem of interpreting these parameters.

For both wheat and barley, the coefficient of variation (Table 3) tends to be greatest with the shortest phases, largely because the reduction in relative precision due to measuring a period length to the nearest day is greatest with those periods having the fewest days. Since the periods were shorter, on the average, for the barley than for the wheat, one might expect greater variation of the k values for barley than wheat, but this was offset by the fact that in the regression analyses in the present study the periods analyzed were from observed stage S_1 to observed stage S_2 wherever possible, rather than from estimated S_1 to observed S_2.

At least part of the difference between the results for barley and wheat was undoubtedly due to the differing response characteristics between the two crops, of which the most obvious is the quicker maturing characteristic of barley. In addition, differences in decisions relating to the selection of procedural details and of parameters during the analysis would also have been a factor.

Olli is an early maturing cultivar of barley that was licensed for sale in Canada in 1936 and is particularly adapted to central and northern Alberta. If biophotothermal time scale analyses were carried out for newer, later maturing varieties, it seems quite possible that the results would be closer to those for Marquis wheat than the results for Olli were.

CONCLUSIONS

Analyses of barley-weather data obtained over five years at nine experimental sites in Canada have provided thresholds and coefficients for a set of equations for estimating the biophotothermal time of five phenological stages of barley from emergence to hard dough, using daily temperature and photoperiod data.

From the results of testing estimates made with the equations against the original data at each stage, and from the coefficients of variation of k, it would appear that the accuracy of biophotothermal time scale estimates for Olli barley, made using the parameters derived here, would be quite similar to that obtained in the Marquis wheat study, providing the conditions in the situations to which they are applied do not differ very much from those represented in the experiments.

Further examination and testing is needed to determine the applicability of the barley equations under other conditions, where the photothermal environment of the crop is much different than any involved in the present study, and the limitations of the model need to be considered in more detail.

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ABSTRACT.- Parameters for an equation representing crop development from planting to emergence, jointing, heading, soft dough and hard dough stages were obtained by iterative regression analysis of five years of temperature, photoperiod, and Olli barley phenological data from nine Canadian locations. The triquadratic model previously developed and applied to Marquis wheat by Robertson was used. The necessity of using the same threshold temperature for both the maximum and the minimum daily temperature causes analysis difficulties and makes the model less realistic. In spite of the model's limitations, the derived parameters are probably quite useful when applied under environmental conditions similar to those represented in the experiment. Under such conditions, the model seems to perform about as well for barley as it did for wheat, in spite of the considerable differences in the development behaviour of the two crops, especially barley's faster rate of development toward maturity.

ZUSAMMENFASSUNG.- Durch wiederholte Regressionsanalyse der Temperature über 5 Jahre, der Photoperiode und der phänologischen Daten für Olli-Gerste an 9 kanadischen Standorten wurden die Parameter für eine Gleichung gewonnen, die das Getreidewachstum von der Saat bis zum Schösslingetreiben, Ährenschieben, und den Stadien der Milchreife und Hartreife wiedergibt. Das triquadratische Modell hat Robertson kürzlich entwickelt und auf Marquis-Weizen angewandt. Die Notwendigkeit, die gleiche Grenztemperatur sowohl für die tägliche Maximum- als auch Minimumtemperatur anzuwenden, erschwert die Analyse und macht das Modell weniger wirklichkeitsnah. Trotz dieser Begrenzungen des Modells sind die abgeleiteten Parameter nützlich, wenn sie unter Umweltbedingungen angewendet werden, die denen im Experiment ähneln. Unter solchen Bedingungen scheint das Modell für Gerste ebenso gut zu sein wie für Weizen, trotz der erheblichen Unterschiede im Entwicklungsverhalten der beiden Getreidearten.

RESUME.- Au moyen d'une analyse par régression itérative on a calculé les poids respectifs de la température et de la photopériode dans une équation représentant le développement de l'orge Olli. Cette équation est applicable aux phases séparant le semis de la levée, la levée du tallage, le tallage de l'épiaison, l'épiaison du stade laiteux et le stade laiteux de la maturité. Pour ce faire, on a utilisé des valeurs tant météorologiques que phénologiques provenant de neuf endroits du Canada et recueillies durant cinq années. On a utilisé le modèle triquadratique développé précédemment par Robertson et qu'il a appliqué au blé Marquis. La nécessité d'utiliser le même seuil de température aussi bien pour le maximum que pour le minimum journaliers cause des difficultés d'analyse et rend le modèle moins réaliste. Malgré les limites du modèle lui-même, les paramètres qui en découlent sont probablement directement utilisables dans des conditions ambiantes semblables à celles ayant régné lors de l'acquisition des valeurs de base. Dans ce cas, le modèle semble aussi bien applicable à l'orge qu'il l'était au blé, bien que les deux cultures se distinguent nettement l'une de l'autre quant à leurs impératifs de développement.