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A DATA BASE FOR PREDICTING SOYBEAN PHENOLOGY*

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WANG J., MCBLAIN B. A., HESKETH J. D., WOOLLEY J. T. and BERNARD R. L. *A data base for predicting soybean phenology.* BIOTRONICS **16**: 25–38, 1987. The quest for a better soybean phenology model continues, phenological behavior being a necessary part of any crop growth and yield simulation model. New and published data for soybean strains from different maturity groups sown at different dates and locations were analyzed for temperature and photoperiod effects on mainstem node appearance rates and on flowering, early pod fill, and maturity dates. Degree days were calculated from maximum and minimum weather station temperatures using 10°C as the base temperature. When the maximum temperature exceeded 28°C, the difference between it and 28 was subtracted from the 24 h degree day calculation. Photoperiods at floral initiation were estimated as those values that occurred 290 degree days before the first open flower, but those that occurred before the longest day of the year were set to the longest photoperiod for the latitude. Such methods for calculating degree days and photoperiods were arrived at from analyses of the literature and by trial and error. Numerous equations and plots are given for predicting the effects of photoperiod and temperature on soybean phenology of Maturity Groups 000–VII. Such information will be used in soybean management models and in planning further phenological research.

Key words: *Glycine max* (L.) Merr.; soybean; phenology; photoperiod; degree days; computer modeling.

INTRODUCTION

Predicting phenological behavior in soybean [*Glycine max* (L.) Merr.] is difficult because of strong photoperiod and temperature effects; for a recent review of

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Table 1. Planting dates, locations, latitudes, soil types, early season mean temperatures, and cooperators for the multilocation experiment, coordinated by B. L. McBlain and R. L. Bernard.

Location	Latitude (°)	(′)	Planting date 1981	1982	Soil type	Mean temperature first 400 DD first model 1981	1982	Cooperator
Ames IA	42	02	26/5	02/6		22	20	D. E. Green, IA S. Univ.
Athens GA	33	37	22/5	22/5	Cecil sand loam		24.4	H. R. Boerma, Univ. GA
Beaumont TX	30	04	19/6	08/6	Morey silt loam	27.6	27.7	G. R. Powers
Blacksburg VA	37	15	11/6	15/6	Glosecose silt	22.2	21.4	B. Buss, VA Agr. UPI-SU
Carbondale IL	37	43	18/6	20/5	Stoy silt loam	24.5	18.5	O. Myers, Univ. IL C.
Dekalb IL	41	57	18/5	13/5	Flanagan silt loam	20	18.6	R. Bell, Univ. IL
Eldorado IL	37	49	22/6	14/5		22	26.3	B. L. McBlain Univ. IL
Guelph Ontario	43	34	01/6	20/6	London silty clay loam	18.5	16.6	D. J. Hume Univ. Guelph
Harrow Ontario	42	02	26/5	22/5	Brady sandy loam	19.8	18.3	R. I. Buzzell Agr. Canada
Isabela PR	18	03	17/6	27/5	Isabela sandy loam	25.8	25.2	J. S. Beaver Univ. P. R.
Lexington KY	38	02	11/6	12/5	Donrail silt loam	23.6	21.3	T. Pfeiffer, Univ. KY
Lincoln NB	40	49	18/5	01/6	Zook silt loam	23.2	21	J. E. Specht, Univ. NB
Ottawa Ontario	45	25	05/6	20/5		20	17.3	H. D. Voldeng, Research Stat.
Portageville MO	36	26	28/5	13/5		25	23.5	S. C. Anand, Univ. MO Delta Ctr.
St. Paul MN	45	00	22/5	22/5	Waukegan silt loam	19.2	18.7	J. H. Orf, Univ. MN
Stoneville MS	33	23	22/5	13/5	Basket fine sandy loam	25.7	25.2	T. C. Kilen, USDA, MAFES
Urbana IL	40	01	29/5 19/6 10/7 31/7	18/5 07/6 01/7	Flanagan silt loam	21.7 22.9 21.6 20.6	19.3 21.1 23.8	B. L. McBlain R. L. Bernard ARS, USDA Univ. IL
Wooster OH	40	46	23/5	02/6	Wooster silt loam	19.9	18.6	R. L. Cooper, USDA, OARDC

Table 2. Days to flowering and maturity as an exponential function of the photoperiod at floral initiation (290 degree days before first flower) and days between first flower and maturity.

Maturity group genotype, stem termination gene dt_1 or Dt_2, all others Dt_1 dt_2; Maturity genes given for clark (C) and Harosoy (H) backross isolines	Dayfw or Daymt$=a+b\times 10^{-6}\times$exp (photoperiod)								
	Exponential models						Days from 1st flower to maturity		
	Days to 1st flower vs. exp (photoperiod)			Days to maturity vs. exp (photoperiod)					
	a	b	R^2	a	b	R^2	Days	SE	n
000,									
Maple Presto	24	1.6	0.33	69	2.8	0.35	52	0.96	79
PI 194–640 (dt_1)	25	1.4	0.32	66	2.7	0.41	49	1.1	73
00,									
Maple Arrow	24	1.7	0.42	76	3.6	0.59	63	0.92	79
PI 189–937	24	1.9	0.50	72	3.7	0.61	60	1.0	78
PI 297–550	25	1.8	0.47	76	3.2	0.56	61	1.0	75
0,									
Evans	26	1.7	0.47	73	4.2	0.70	64	1.3	74
I (e_1 e_2 e_3),									
L72–1543 (H)	26	1.7	0.52	77	4.4	0.67	67	1.1	75
L71–920 (C)	26	1.8	0.52	81	3.9	0.63	68	0.93	75
Hodgson	25	1.8	0.55	77	4.2	0.67	66	1.2	75
II (e_1 e_2 E_3),									
L65–778 (C, dt_1)	26	1.8	0.55	79	4.3	0.63	68	1.2	74
L62–364 (H, Dt_2)	25	2.1	0.62	78	4.4	0.70	66	1.1	73
L67–153 (H, dt_1)	25	2.0	0.64	75	4.6	0.68	66	1.2	71
L63–3117 (C)	26	2.0	0.63	83	4.3	0.66	69	1.0	73
Harosoy (H)	27	2.1	0.55	81	4.2	0.66	67	1.1	71
Wells II	24	2.5	0.68	78	4.5	0.68	66	1.0	73
III (e_1 E_2 e_3),									
L64–2404 (C)	25	3.0	0.78	83	5.2	0.72	72	1.1	72
PI 317–334B	27	3.2	0.71	82	5.4	0.75	69	1.1	73
Elf (dt_1)	25	3.0	0.83	84	5.5	0.79	73	1.1	71
Williams	26	3.2	0.79	86	5.2	0.79	73	1.0	69
Will (Dt_2)	24	3.3	0.78	82	5.3	0.80	71	1.0	71
L76–3344 (C)	28	1.8	0.63	83	4.7	0.67	71	1.2	73
L76–3232 (C)	25	2.2	0.65	81	4.2	0.70	68	0.85	73
IV (e_1 E_2 E_3),									
Clark (C)	25	3.4	0.83	89	5.3	0.80	75	1.1	69
L74–21 (H)	26	3.1	0.72	85	5.6	0.79	72	1.1	64
L63–3016 (C, dt_1)	26	2.8	0.75	87	5.5	0.76	77	1.3	69
L62–1251 (C, Dt_2)	26	3.2	0.82	85	5.6	0.81	74	1.1	69
Kent	30	3.4	0.80	92	5.7	0.78	75	1.2	56
L64–4548 (H)	25	3.8	0.76	85	6.0	0.80	74	1.2	65
IV–V (E_1 e_2 E_3),									
L71–1363 (C, Dt_2)	26	5.6	0.76	83	7.0	0.83	67	1.2	59
L66–531 (C, dt_1)	27	4.6	0.75	83	6.4	0.77	67	0.9	67
L66–432 (C)	29	4.7	0.74	89	6.1	0.77	69	0.94	65
L71–1116 (H)	21	6.3	0.75	75	8.1	0.82	69	0.93	65
L67–2324 (H, dt_1)	25	6.6	0.59	87	6.9	0.67	66	1.0	61
L74–59 (H, Dt_2)	24	6.6	0.71	82	7.8	0.79	67	1.1	63

Table 2. (Continued)

Maturity group genotype, stem termination gene dt_1 or Dt_2, all others Dt_1dt_2; Maturity genes given for clark (C) and Harosoy (H) backcross isolines	Dayfw or Daymt $=a+b\times10^{-6}\times\exp$ (photoperiod)								
	Exponential models						Days from 1st flower to maturity		
	Days to 1st flower vs. exp (photoperiod)			Days to maturity vs. exp (photoperiod)					
	a	b	R^2	a	b	R^2	Days	SE	n
(E_1 E_2 e_3)									
L74–441 (C)	28	6.7	0.61	92	7.0	0.70	69	1.0	53
(E_1 e_2 e_3)									
L80–5917 (C)	27	4.1	0.72	85	5.7	0.81	68	0.87	67
L80–5918 (C)	30	3.5	0.64	84	5.9	0.81	69	0.88	66
L80–5923 (C)	30	3.4	0.69	85	5.5	0.82	68	0.98	69
L80–5931 (C)	27	3.9	0.75	84	5.7	0.82	68	0.94	71
V, (E_1 E_2 E_3)									
L66–546 (C, dt_1)	23	8.8	0.72	95	7.6	0.51	71	1.4	43
L65–3366 (C)	24	9.8	0.71	96	8.5	0.62	70	1.0	44
L73–980 (C, Dt_2)	27	10.5	0.62	101	8.0	0.56	71	1.0	45
Forest (dt_1)	27	9.7	0.59	97	9.1	0.64	74	1.3	39
VI, Tracy	30	11.2	0.63	95	12.7	0.61	74	1.8	35
VII, Bragg	49	10.0	0.36	117	8.7	0.21	68	2.5	10

the problem, see Summerfield and Roberts (*13*). Soybean growth and yield models depend upon good predictions of phenological events such as the beginning of flowering, early pod fill and maturity. Numerous models have been developed, based upon field and controlled data (*6*, *7*, *11*). We report here a new multi-location data set, with further analyses of results from date-of-planting experiments published earlier. The objective of the new study was to relate V-stages or main-stem node numbers and degree days at flowering to photoperiod; models might use the degree day requirement for a phenological event directly or might use a degree day model to predict the V-stage at a phenological event. The data were taken in 1981–82; we have been analyzing these and published results since then. This paper summarizes the state of our analyses as of late 1987; the data set may well be the subject of more papers as our understanding of the thermal and photoperiod processes involved improve.

MATERIALS AND METHODS

Locations, latitudes, soil types, planting dates and cooperators are listed in Table 1. Seeds of 46 soybean strains (see Table 2) supplied by the ARS-USDA Soybean Germplasm Lab., Urbana, IL, were sown at 18 locations for two growing seasons. The date, height, and V-stage at the beginning of flowering and at maturity (or frost) were recorded. R-stages were recorded at frost. Weather station records and the data were turned over to the Urbana cooperators for analyses. 'Clark' and 'Harosoy' backcross isolines differing in maturity (E_1e_1, E_2e_2, E_3e_3) and stem termination (dt_1Dt_1, dt_2Dt_2) genes (Bernard, *1*) were included in the test.

Degree days were calculated from the weather records of maximum and minimum temperatures, using 10°C as the base temperature, or [[(maximum+minimum temperature)/2]−10] with negative values set to 0. Until recently, degree day values per day above a mean temperature of 30°C were set to 20; this will be referred to below as our first modified degree day model. Such degree day values plotted poorly against photoperiod, with large variations at the lower latitudes. A reviewer, T. Hodges (*6*) at Prosser, WA, U.S.A., suggested substracting thermal units from the daily total above a temperature optimum. We searched for such an optimum and a temperature dependent reduction factor and settled upon 28°C as the temperature optimum and [the daily maximum temperature value minus 28, if it were greater than 28], as the reduction factor. It was obvious from inspection of the data that degree day values at the lower latitudes had to be decreased somehow; our correction factor accomplished that; whereas similar models with the temperature optimum set at 29 or 30°C did not.

Photoperiods were calculated for each day, including the time that the sun was higher than four degrees of arc below the horizon. This approximates the time during which the illuminance is 20 lux or more (photosynthetic photon flux density >350 nmol m^{-2} s^{-1}). Based upon the degree day requirement for growing a floral bud from initiation to opening as reported by Jones and Laing (*7*), we determined the photoperiod for floral initiation at 290 degree days before the first open flower.

Progress in finding relationships correlating phenological events with photoperiod was slow; at one stage data from the date-of-planting experiment at Urbana was analyzed separately, pooling data for strains of the same maturity group. More strains were included in the Urbana experiments; for our analyses, data were pooled among strains within maturity groups as follows: Maturity Group (MG) 000—'Maple Presto'; MG 00 —'Maple Arrow', 'Portage', 'McCall' and 'Altona'; MG 0—'Wilkin', 'Swift', 'Evans', and 'Clay'; MG I—'Weber', 'Coles', 'L73-1543', 'L71-920', 'Hodgson', 'Hardin', 'Harlon', and 'Steele'; MG II—'Harosoy', 'Beeson 80', 'Amsoy 71', 'Century', 'L63-3117', 'Wells II', 'Harcor', 'Amcor', and 'Corsoy 79'; MG III—'Woodworth', 'Williams', 'Pella', and 'Cumberland'; MG IV—'Crawford', 'Union', 'Cutler 71', 'Columbus', 'L76-3324', 'Clark', 'Franklin', 'Bonus', 'Desoto', and 'Kent'; MG V—'L65-3366', and 'Bedford'. A few obviously 'bad' measurements were deleted from the analysis.

Photoperiods and degree days were also calculated for date-of-planting results reported earlier (*3*, 5, *8–12*); Cregan and Hartwig's data (*2*) were also reanalyzed. These data were analysed in the same manner as the multi-location results; progress in analyses were frequently made first with the literature data.

RESULTS AND DISCUSSION

Multi-location study

Degree days per V-stage was calculated for each experiment from regressions among strains of V-stages vs. degree days at flowering. Such values are plotted vs. latitude for each experiment, Fig. 1. The range in V-stages at flowering should increase and water stress should decrease with increasing latitude, resulting in an

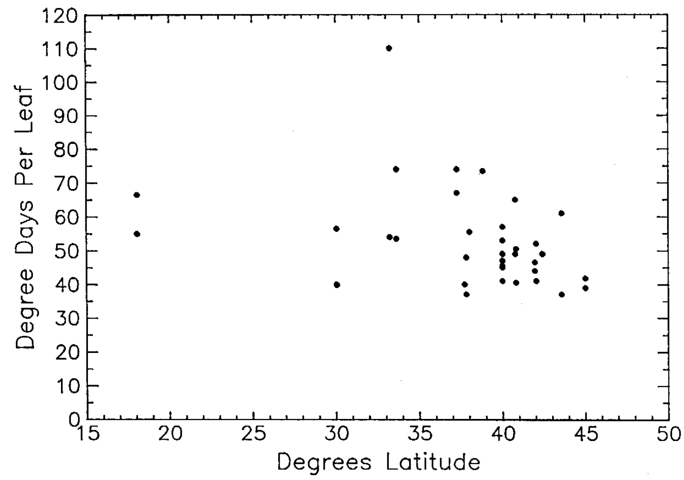

Fig. 1. Modified degree days [[[(maximum+minimum temperature)/2]−10] minus [maximum temperature −28] if the maximum temperature was greater than 28] per leaf or V-stage vs. latitude for the 18 experimental sites. Water stress and a limited range in V-stage values under short days at the lower latitudes are probably responsible for much of the scatter, see discussion in the text.

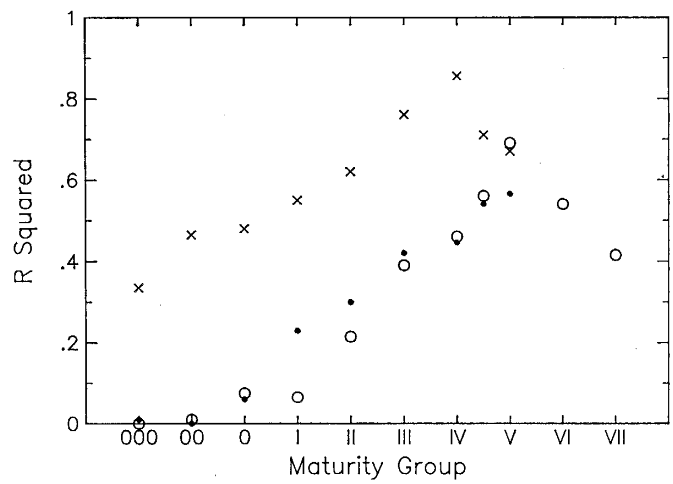

Fig. 2. A summary of R^2 values for a regression analysis of days (×), V-stages (●) and degree days (○, second modified model, see Fig. 1 caption) vs. $10^{-6} \times \exp$ (photoperiod at floral initiation).

improvement in estimates of degree days required per V-stage. The scatter indicates the problem one faces when attempting to predict V-stage using a degree day model. R^2 values for such regressions were quite high; however, R^2 values for V-stage vs. days were equally high. The mean temperature for the first 400 uncorrected degree days varied from 16.7 to 27.7, Table 1, indicating the need for a degree day model.

Despite the fact that plants are known to respond to night length rather than day length, and despite the fashion among modelers and others to plot rates of progression to flowering as 1/days or 1/(degree days), we chose to plot the time or ther-

Table 3. Date-of-planting experiment, Urbana, 1981–1982.
Summary of phenology models

MG*	Equation, $a+b\times10^{-6}\times\exp$ (photoperiod at floral initiation)											
	Nodes at R_1			Nodes, R_1 to R_5			Degree Days to R_1			Days to R_1		
	a	b	R^2	a	b	R^2	a	b	R^2	a	b	R^2
000	2.97	0.304	.23	−0.169	1.07	.93	339			32		
00	3.75	0.224	.51	−0.033	1.19	.88	324			31		
0	4.16	0.179	.45	1.8	0.63	.89	315			30		
I	3.9	0.33	.69	−1.64	1.72	.87	331	5.2	.11	31.8	0.384	.01
II	4.23	0.298	.65	−2.48	1.86	.87	342	7.4	.26	31.9	0.709	.50
III	3.85	0.708	.88	1.57	1.33	.73	326	18.75	.74	31.6	1.62	.29
IV	2.98	1.12	.83	1.90	1.31	.88	331	27.4	.94	32.2	2.41	.55
V	4.97	2.23	.92	3.37	0.90	.85	366	88.3	.78	40.4	6.49	.85

MG*	Equation, $a+b\times10^{-6}\times\exp$ (photoperiod at 1st flower)					
	Nodes, R_1 to R_5			Nodes at R_5		
	a	b	R^2	a	b	R^2
000	3.37	0.615	.83	6.82	0.894	.87
00	3.61	0.809	.86	7.95	0.982	.90
0	2.93	0.902	.73	7.58	1.04	.79
I	3.12	1.31	.93	7.93	1.54	.95
II	2.93	1.14	.92	8.33	1.70	.95
III	4.81	1.18	.85	10.54	1.72	.87
IV	5.18	1.19	.76	10.83	2.25	.87
V	3.57	1.78	.56	11.58	5.22	.78

*MG=Maturity Group

mal time required for flowering vs. the daylength. The V-stage at flowering and days or degree days from planting to flowering plotted best against the exponential of the estimated photoperiod value at floral initiation. R^2 for such plots increased with maturity group up to Maturity Group V, Fig. 2. R^2 values were higher for the real time plots (Table 2); however, temperature and photoperiod were not independent with latitude. Warm temperatures and shorter days at the lower latitudes reduced the time required for flowering to begin; whereas cold temperatures and longer days at the higher latitudes increased the time required. These effects contributed to the goodness of fit of the equation for days plotted against the exponential photoperiod. Our goal was to account for temperature effects within a location; hence we tried to improve the fit for degree days or V-stages vs. the exponential of photoperiod. R^2 values for V-stages vs. the exponential of the photoperiod are obviously unaffected by methods for calculating degree days and the values we present are those encountered in our original analyses in 1984. However, water stress is known to affect the V-stage at flowering much more than the time or degree days to flowering; therefore, one might hope to encounter better R^2 values for degree days vs. photoperiod. Figure 2 summarizes our most recent efforts; however, first we set out to analyze the Urbana location data, which included dif-

Table 4. Degree days (base 10°C, Temperature>30°C=30) to first flower or maturity. Data for locations north of Urbana, IL, or 40 latitude. Degree days to event=$a+b\times$(mean temperature). Event A=first flower. Event B=maturity. n=24.

Maturity group	Genotype	Event	a	b	R^2
000	Maple Presto	A	−302	34.6	0.76
		B	−659	80	0.80
00	Maple Arrow	A	−330	36.8	0.86
		B	−570	84	0.89
	PI 297–550	A	−231	33.2	0.92
		B	−533	83.1	0.92
0	Evans	A	−205	32	0.89
		B	−411	77.8	0.81
I	Hodgspm	A	−448	45.4	0.83
		B	−471	84.6	0.89
	L71–920 (C)	A	−106	27.1	0.60
		B	−671	93.1	0.92
	L73–1543 (H)	A	−178	30.7	0.72
		B	−488	84.2	0.94
	PI 189–937	A	−160	29.4	0.71
		B	−388	74.5	0.82
II	Harosoy (H)	A	−407	44.6	0.82
		B	−365	81.3	0.81
	L63–3117 (C)	A	−315	39.4	0.71
		B	−749	99.3	0.92
	L67–153 (C, Dt_2)	A	−329	39.6	0.71
		B	−529	86.4	0.86
	L65–778 (C, dt_1)	A	−325	38.7	0.83
		B	−774	98.7	0.9
	Wells II	A	−334	41.8	0.71
		B	−545	88.9	0.89

C=Clark background. H=Harosoy background. dt_1=determinate. Dt_2=semi-determinate.

ferent dates-of-planting. The results of regressing various Urbana parameters against the exponential of the photoperiod are shown in Table 3, where degree days to R_1 (first flower) works as well as real days to R_1. Also node or V-stage plots gave high R^2 values. Uncorrected degree day values worked even better (results not shown). It was tempting at this point to include data from nearby locations in this analysis but we did not get far with this approach; however, these results inspired us to search for a better degree day model for the multi-location data set, which we will describe below.

First, using the first model for calculating degree days, degree days to R_1 and R_8 (maturity) also regressed well against the mean temperature during the relevant growth period for the latitudes north of Urbana (40°), Table 4. Of course, maximum temperatures were rarely much above 28°C at these latitudes. At this point, we felt we had logic for predicting flowering at the higher latitudes. However, we may have searched for a modified degree day model that would eliminate the seasonal temperature effect. Such a model wouldn't improve our predictions but might

Table 5. Maturity Group or strain parameters for degree days from planting to first flower vs. the exponential of the estimated photoperiod at floral initiation [$Y=a+b\times 10^{-6}$ exp (photoperiod)].

Maturity Group	Plant material	a	b ($\times 10^{-6}$)	R^2	n
00	Maple Arrow	345	−0.1	.0	83
0	Evans	347	2.9	.05	78
I	Hodgson	349	4.1	.07	84
	L71–920 (C)*	362	3.1	.04	85
II	Harosoy (H)	381	5.1	.06	84
	Wells II	352	8.8	.19	85
	L63–3116 (C)	373	4.55	.08	85
III	Williams	387	14.6	.38	84
	Will (Dt_2)	365	14.9	.39	84
	Elf (dt_1)	380	14.9	.43	86
IV	literature	370	21.7	.43	21
	Clark (C)	362	19.3	.55	82
IV-V	L74–441 (C)	426	40.7	.66	79
	L80–5931 (C)	396	21.1	.55	79
	L80–5918 (C)	429	17.5	.50	80
	L80–5913 (C)	376	20.4	.56	84
	L66–432 (C)	427	27.65	.59	86
	L67–2324 (H, Dt_2)	384	42.6	.66	83
	L71–1116 (H, dt_1)	392	41.5	.54	85
V	literature	314	85.5	.55	37
	L65–3366 (C)	451	54	.75	75
	L66–546 (C, dt_1)	432	50	.63	81
	L73–980 (C, Dt_2)	469	59	.54	86
	Forest	439	61.1	.58	81
VI	literature	248	151	.93	28
	Tracy	491	70	.54	77
VII	literature	319	117	.77	21
	Bragg	490	77/106	.41	60

*C=Clark backcross isoline; H=Harosoy backcross isoline.

indicate how the soybean plant responds to temperature; we did not have the time of resources for such a search.

Table 5 gives equations and R^2 values from a regression analysis of our degree day values calculated using our second modifed degree model vs. the exponential of the estimated photoperiod at floral initiation (the literature results will be discussed below). The R^2 value for the L65-3366 plot increased from 0.52 to 0.75, when going from the first to the second modified degree day model. The second modified degree day model also worked well with earlier phytotron results (*10*); when nothing else had, as we shall see below.

Results given in Fig. 2 and Table 5 indicate how well a thermal-photoperiod model can predict phenology among Maturity Groups; such models obviously should work well for Maturity Groups V and greater.

Thus far we have only discussed predicting the date for the first flower. Table 3 shows the strong effect of photoperiod on mainstem nodes produced from R_1 to

Table 6. Regression equations for flowering: photoperiod data from the literature. Days to 1st flower$=a+b\times 10^{-6}\times$exp (photoperiod 20 days prior to 1st flower, or that for the longest day of the year if the value at 20 days prior to 1st flower occurred before the longest day)

Source	Genotype	MG	a	b	R^2	n
McBlain,	several	V	28.4	7.5	.63	30
others		VI	19.95	15.7	.78	30
		VII	27.26	13.4	.48	22
Lawn, Byth	Dorman	V	33.5	4.83	.34	20
	Semistar	VIII	18.4	18.7	.90	20
	K162	IX	22	30.6	.99	20
	Gilbert	X	23.5	37.4	.90	20
	K8	XI	12.7	86	.98	20
Cregan,	Fiskiby	00	24.9	0.0086	.51	8
Hartwig	Maple Arrow	00	27.6	0.0344	.80	8
	Williams	III	34.4	0.1107	.78	8
	Hill	V	41.4	1.97	.91	7
	Forrest	V	40	2.49	.94	7
	Tracy	VI	38.7	3.02	.78	7
	Biloxie	VIII	45.4	7.96	.71	6
	PI 159925	VIII	63.2	4.7	.74	6
	Jupiter	IX	38.7	25.36	.94	3
	PI 274454	X	44.7	81.1	.97	3

MG=Maturity Group

R_5, indicating the effects of photoperiod on physiological time to R_5 or the early pod fill growth stage. Tables 2 and 4 show effects of photoperiod on time to maturity. Better relationships were derived from the Urbana and published date-of-planting studies, which we will now discuss.

Date-of-planting studies, a reanalysis

For the published results, days to flower vs. the estimated photoperiod at floral initiation varied more among locations than within, Table 6. Degree days to first flower worked as well for the published data, including the 1981–82 date-of-planting Urbana data, as it did for the multi-location data set, Table 5. Data were combined from three to five sites for this analysis, depending upon the cultivar. Cultivars for each MG differed from site to site; V- and R-stages were defined somewhat differently. As in the case of the data set reported above, different people made the growth stage measurements. Time rarely permitted precisely pinpointing the date when 50% of the plants were at a specific phenological stage. Considering these limitations, the goodness of fit of our equations to the data are encouraging.

Jones and Laing (7), using natural daylengths in their controlled temperature studies, encountered variability in time from planting to first flower for a particular daylength, depending upon whether flowering occurred before or after the longest day of the year. The time to first flower was longer before the longest day than after. We avoided some of this variability in all our analyses by setting the daylength to the longest day for the latitude if an event occurred before the longest day. This was not too much of a problem in our multi-location study where most experiments

Table 7. Linear regression equations for effects of photoperiod on the time from flowering to early pod fill or maturity and the time from early pod fill to maturity, data taken from the literature [days$=a+b\times$(photoperiod)].

	MG	a	b	R^2	n
Time from 1st flower to maturity	II	-13.5	5.2	.0	7
vs. photoperiod at flowering,	III	-51	8.1	.70	7
(time, R_1 to R_8), Urbana data	IV	-62	8.8	.62	7
A: Time from 1st flower to early	IVA	-128	10.9	.28	13
pod fill (time, R_1 to R_5)	B	15.2	3.83	.59	13
B: Time from early pod fill to	VA	-91	7.94	.67	29
maturity (time, R_5 to R_8)	B	52.4	8.22	.64	22
	VIA	-138.7	11.75	.86	29
	B	-121.3	13.9	.66	22
	VIIA	-161	13.6	.88	23
	B	-153	16.7	.87	15
	VIIIA	-158	13.5	.85	17
	B	-325.5	29.6	.89	10

Photoperiod for A=mean of that at 1st flower and that 20 days later.
Photoperiod for B=mean of that at early pod fill and that 40 days later. MG=Maturity Group

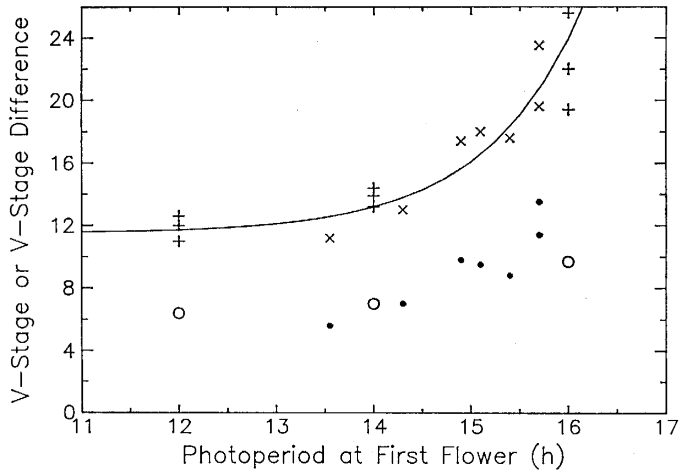

Fig. 3. V-stages at early pod fill for Maturity Group III strains grown under field (×) or controlled conditions (+, see McBlain *et al.*, 1987) and the V-stage difference between early pod fill and first flower for field (●) and controlled (○) conditions plotted vs. the photoperiod at flowering. The equation for all the early pod fill V-stage data was V-stage$=11.4+[1.4\times10^{-6}\times\exp$(photoperiod at flowering)], $R^2=0.84$.

were planted late enough to minimize the occurrence of such an effect. In the Kruse *et al.* (*8*) experiment, the thermal requirement for flowering in the early plantings seemed to respond to the prevailing short days that occurred long before June 21 invalidating our practice of setting all day lengths before the longest one to that at June 21 (or December 21 for the Lawn and Byth (*9*) data).

Predicting the flowering date does not lead to a good prediction of the maturity

Table 8. Comparisons of degree days and days from planting to flowering between Maturity Group V stains grown in the field and those grown under controlled conditions.

Strain	Photoperiod (h)					
	Degree Days			Days		
	12	14	16	14	15	16
L65–3366	460	516	931	36	56	111
Mean, 3 others*	456	557	950	36	56	112
Literature results	328	416	1073	39	53	95
McBlain, Phytotron						
32/23**	386	432	970	36	—	81
23/20	355	491	867	45	—	79
32/29	600	675	1072	42	—	67
32/17	378	526	1000	66	—	125
McBlain, Field	441	570	876	48	—	84
Lawn, Byth				40	49	76
Cregan, Hartwig				48	52	65

* Mean, 3 others are from Tables 2 and 5. Literature results are from Table 6. See REFERENCES for the other sources.

** 8 h/16 h temperature regime (°C), 16 h photoperiod.

date; the time from R_1 to R_5 is well known to be sensitive to photoperiod (*13*). We were able to correlate days from R_1 to R_5 with the mean photoperiod during this period, Table 7; whereas degree days from R_1 to R_5 did not correlate well (analyses not shown).

Comparing results from controlled vs. natural conditions

Figure 3 shows a comparison of V-stage values for field and controlled conditions, for Maturity Group III strains; Table 8 shows the same comparison for degree day and day values for Maturity Group V strains. We had questioned the validity of using results from artificial photoperiods to predict how the plant responds to natural photoperiods; the comparisons we show seem to validate the use of information from controlled environments, depending upon how one wants to interpret the differences shown.

The phenology model

Jones and Laing (*7*) and Mishoe *et al.* (*11*) have developed physiological process models for predicting soybean phenology; Hodges and French (*6*) published a phenological model based upon logic similar to what we have derived here. Our data base can be used to calibrate these models better or improve the logic involved. If one could relate V-stages for phenological events to photoperiod, one could use a V-stage degree-day model to predict calender dates, using accumulated weather data for the season in question and historic or predicted data for projections into the future. However, as we have shown (Fig. 1), it may be difficult to predict the degree day requirement for a V-stage increment. One can use the degree day relationships we have derived, as we are in the process of doing, to predict the date for floral initiation and flowering. We are subtracting 290 degree days from such relationships to get the requirement for floral initiation, and are using the real time: photoperiod relationships to predict the time from flowering to early pod fill and from then to maturity.

For communication to other experimentalists we have used daylength and duration between events, rather than nightlength and 1/duration, in our equations and plots. The latter transformations in data are routinely made by those involved in the development of logic for plant growth models.

Plans are in progress in the U.S.A. for further phenological studies such as we described. One should be encouraged rather than discouraged by our new results. Careful measurements of the timing of flowering, early pod fill and maturity for a few representative cultivars from the various Maturity Groups at fewer locations might be sufficient. Careful records of available soil moisture are needed to determine affects of water stress on phenology. Plant spacing and fertility must be accounted for. Varying the planting date seems to give good results. It might be useful to develop a better indicator of a V- and R-stages. The appearance of a 10 mm long leaf at the shoot apex is easy to determine and its phylochron, or thermal time between the appearance of successive 10 mm leaves on the main shoot, is reasonably independent of plant age or reproductive processes. One should, of course, always calibrate against the standard phenological index in use.

At Urbana, V-stages rarely exceed 28, and under the right conditions (early planting, a warm spring) such values can be obtained for cultivars adapted to that location. Because of this behavior and perhaps other confounding factors, differences in time or thermal time to a phenological event are not always reflected as differences in V-stages, particularly among late maturing strains not adapted to a particular latitude.

When the expression of such values are important for comparisons to be made, such plants should be well spaced from each other. In fact, in most V-stage studies, values for stunted plants growing under crowded conditions only contribute to the error term. One should be a bit cautious in planning such experiments as they are time consuming and, like all field experiments, are subject to unpredictable factors during a growing season that can ruin an experiment.

Despite the problems mentioned above, the overall approach revitalizes the usefulness of field plot research for quantifying phenological processes. A good record of local weather conditions, with rainfall determined at the plots, is essential, along with an ability to use, study, and improve a sophisticated standard phenological index. Effects of the environment on the duration of floral bud growth much also be accounted for; results from controlled environments on this and other associated processes are needed. As such, the overall approach should involve both field and controlled environment research.

Modeling philosophy

Previous investigaters have taken a similar research approach to developing a soybean phenology model, and in doing so have made good progress. Some of the authors have been working on this problem since 1972 (*4*), and have been under a mandate for some 10 years to develop an improved model. We are convinced that further research and synthesis are needed before soybean plant growth and yield models become credible, but we are pleased with the progress that we and others have made in developing the necessary quantitative logic, as evident in the recent literature; however, it must be apparent from our results here that much more needs to be done. We currently are using our phenology model to predict and study canopy leaf area expansion and senescence.

Such a research approach is essential for studying how cropping systems behave or whole plant physiology in general. However, research resources must be committed to it with caution to minimize any interference with the research process.

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