Agricultural and Forest Meteorology, 43 (
Elsevier Science Publishers B.V., Amsterdam — Printed in The Netherlands

ESTIMATION AND EVALUATION OF WINTER WHEAT PHENOLOGY IN THE CENTRAL GREAT PLAINS*

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(Received June 8, 1987; revision accepted September 19, 1987)

ABSTRACT

McMaster, G.S. and Smika, D.E., 1988. Estimation and evaluation of winter wheat phenology in the central Great Plains. Agric. For. Meteorol., 43: 1-18.

Crop modeling and management requires accurate prediction of crop phenology. Phenology data for winter wheat (*Triticum aestivum* L.) were collected from seven sites in the central Great Plains for several years to relate phenological stages to environmental and cultural factors, and to provide needed phenology data for the central Great Plains.

Number of calendar days (*ND*), growing degree-days (*GDD*), and photothermal units (*PTU*) were calculated for emergence (E), tiller initiation (TI), dormancy end (DE), jointing (J), heading (H), kernel in milk (KM), kernel in hard dough (KD), and maturity (M) using the Feekes growth scale for the main stem. Nine base temperatures (−2, 0, 1, 2, 3, 4, 5, 7, and 9 °C) were used when accumulating *GDD* and *PTU*. Mean daily temperatures of 20, 25, and 30 °C were used for upper thresholds. Accumulation of *GDD*, *PTU* and *ND* were calculated from planting date (S), E, and 1 January to the growth stage and from one growth stage to the next. Model sensitivity to soil water, cultivar, seeding rates, row spacing, rotation, and fertilizer were examined.

The lower the base temperature for a model, the lower the root mean square error (*RMSE*) when beginning accumulation from S, E or 1 January, with −2 °C the best except for DE, KD, and M where higher base temperatures tended to have lower *RMSE*. As M was approached, the 25 °C upper threshold tended to do better than 20 °C. Little difference was found between 25 and 30 °C upper thresholds. The best model for predicting a stage varied, with *ND* the best for E through J. From H through M, *PTU* models had the lowest RMSE. Normally, *GDD* and *PTU* models beginning accumulation from 1 January outperformed models beginning accumulation from S or E. The *GDD* or *PTU* related to availability of soil water showed a parabolic relationship (concave downward) beginning at J and becoming more platykurtic as M was approached. Significant sensitivity to cultivar and row spacing/rotation was found, with occasional sensitivity by various model types found to fertilizer and planting date.

*Contribution from Northern States Area, Agricultural Research Service, U.S.D.A.

0168-1923/88/$03.50

INTRODUCTION

Interest in modeling and crop condition assessment has spurred renewed interest in estimating phenology. The primary focus has been on growing degree-day approaches (Nuttonson, 1948; Nuttonson, 1955; Wang, 1960; Robertson, 1968; Maas and Arkin, 1980; Rickman et al., 1983; Ritchie and Otter, 1985). Diverse base temperatures have been used making comparison among studies difficult, and rarely have studies used negative base temperatures or incorporated an upper threshold value. To improve predictive accuracy, daylength has been added to generate photothermal unit models. Several reviews have evaluated the success of these models (Heuer et al., 1978; Hodges and Doraiswamy, 1979; French and Hodges, 1985), but the available data bases were limited, and few phenology data are available from the central Great Plains, particularly for modern cultivars.

Although temperature and light are the major factors controlling phenological development, diverse environmental factors, cultural practices, and cultivar differences may also influence phenology. Factors other than temperature and light have confounded comparison among studies: conflicting results have been reported on the influence of soil water, nutrient content, cultivar, planting date, plant density, and rotation on phenology (Wang, 1960; Robertson, 1968; Mor and Aggarwal, 1980; Davidson and Campbell, 1983; Singh et al., 1984; Bauer et al., 1984b). The mechanism of action for many of these factors can partly be attributed to the direct or indirect effect of temperature and light conditions. Sensitivity of phenological models to environmental and cultural conditions has rarely been explored. The objective of this study was to obtain the best possible estimate of the number of calendar days (*ND*), growing degree-days (*GDD*), and photothermal units (*PTU*) required to reach different winter wheat (*Triticum aestivum* L.) phenology stages, using a range of base temperatures and upper thresholds, for sites throughout the central Great Plains. Each approach was then evaluated, and model sensitivity to soil water availability, fertilizer, planting date, cultivar, and row spacing/rotation was tested.

METHODS

Seven field sites were selected throughout the central Great Plains: various physical and cultural characteristics of each site are presented in Table 1. A more detailed description is by Smika (1985). Hourly maximum and minimum air temperature 2 m above the soil surface, solar radiation, precipitation, wind speed, and vapor pressure were measured (Duke and Blue, 1985; Heermann et al., 1985). Three to five times during the growing season gravimetric soil water content was measured for each site to 1.8 m depth with 12 replicates per site at each sampling.

TABLE 1

Identification and description of the nineteen data sets collected. The sites are named for the closest city

Field site	Akron, Colorado	Medford, Oklahoma	Albin, Wyoming	Paxton, Nebraska	Mankato, Kansas	Tribune, Kansas	Garden City, Kansas
County Name	Washington	Grant	Banner (NE)	Keith	Jewel	Greeley	Finney
Elevation (m)	1372	376	1463	988	543	1105	892
Latitude	40°09′55″	36°52′41″	41°27′48″	41°01′48″	39°49′25″	38°27′09″	38°09′09″
Longitude	102°59′16″	97°40′19″	103°59′43″	101°24′52″	98°15′00″	101°47′04″	100°46′07″
Cultivar	Centurk	Tam 101	Scout 66	Centurk	Scout 66	Larned	Centurk
Rotation	wheat-fallow	continuous wheat	wheat-fallow	wheat-fallow	continuous wheat	wheat-fallow	wheat-fallow
Row spacing (m)	0.30	0.18	0.30	0.30	0.18	0.30	0.30
Seeding rate ($kg\ ha^{-1}$)	33.6	67.2	67.2	50.4	67.2	22.4	33.6
Nitrogen fertilizer at seeding ($kg\ N\ ha^{-1}$)	44.8	100.8	0.0	67.2	100.8	0.0	67.2
Soil type	Platner sandy loam (Aridic Argiustoll)	Renfrow silt loam (Udic Argiustoll)	Rosebud loam (Aridic Argiustoll)	Daws very fine sandy loam (Typic Argiustoll)	Harney silt loam (Udic Argiustoll)	Richfield silt loam (Aridic Argiustoll)	Ulysses silt loam (Typic Argiustoll)
Organic matter (%)	1.2	2.4	1.0	0.8	2.0	0.9	1.1
pH	7.4	6.6	7.9	7.2	6.9	7.6	7.6
Planting date:							
1977	4 Sept	28 Sept	27 Aug	14 Sept	24 Sept	9 Sept	19 Sept
1978	12 Sept	27 Sept	29 Aug	16 Sept	10 Oct	8 Sept	
1979	10 Sept		25 Sept	23 Sept		16 Sept	17 Sept
1980	20 Sept						

Growth stages were estimated on ten randomly selected main stems several times weekly, except at the Albin, WY location which was visited only weekly. The Feekes growth stage scale (Large, 1954; Bauer et al., 1983; Bauer et al., 1984a, 1984b) was used, with the stipulation that at least half of the main stems must have reached the growth stage before declaring that stage to be reached. The tested stages and associated Feekes growth stage number were: seeding (S, 0.0), emergence (E, 1.0), tiller initiation (TI, 2.0), dormancy end (DE, 3.0), jointing (J, 6.0), heading (H, 10.3), kernel in milk (KM, 10.54), kernel in hard dough (KD, 11.3), and maturity (M, 11.4).

Three general model types were evaluated: number of calendar days (ND), growing degree-days (*GDD*), and photothermal units (*PTU*). *ND* is the number of inclusive calendar days from one growth stage to another.

Growing degree-days (*GDD*) are generally defined as

$$GDD = \sum_{i=s_1}^{s_2} [TAVG_i - TBASE] \tag{1}$$

where *TBASE* is a threshold or base temperature, *i* is the day beginning at growth stage s_1 and incrementing daily until the beginning of growth stage s_2, $TAVG_i$ is the average 24-hour temperature from 0 to 24.00 hours computed from:

$$TAVG_i = \frac{T_{\max} + T_{\min}}{2}$$

Occasionally, an upper threshold will be included so that if $TAVG_i$ is greater than the threshold, $TAVG_i$ is set equal to the threshold.

To compute photothermal units (*PTU*), daylength is included in eq. 1:

$$PTU = \sum_{i=s_1}^{s_2} L_i \, [TAVG_i - TBASE] \tag{2}$$

where L_i is the daylength for day *i*. Daylength is defined as the period from sunrise to sunset and is estimated using the algorithm from Baker et al. (1985).

In this study, nine base temperatures were used to compute *GDD* and *PTU*: −2, 0, 1, 2, 3, 4, 5, 7, and 9°C. Mean daily temperatures ($TAVG_i$) of 20, 25, and 30°C were used for upper thresholds. Two general submodels of the *GDD* and *PTU* models were tried depending on whether or not the temperature was reset because the base temperature or upper threshold was exceeded. One set of submodels reset $TAVG_i$ equal to *TBASE* or the upper threshold whenever $TAVG_i$ exceeded *TBASE* or the upper threshold. These submodels were designated by G or P to indicate the *GDD* or *PTU* model, Y to signify that the temperatures could be reset, and a number representing the upper threshold value. The base temperature was inside parentheses when appropriate. An example is GY20(−2) which denotes the *GDD* model and that $TAVG_i$ was reset

(=Y) if below the $-2\,^{\circ}$C base temperature or above the 20 °C upper threshold. Submodels where $TAVG_i$ was not reset if less than the base temperature or greater than the upper threshold are designated as GN and PN for the *GDD* and *PTU* models, respectively. Four approaches were used in accumulating *GDD* and *PTU* for a particular growth stage: (i) from seeding to growth stage s_i, (ii) from emergence to growth stage s_i, (iii) from 1 January to growth stage s_i, and (iv) for successive growth stages (s_i to s_{i+1}).

Each model was run using the 19 data sets. The *ND*, *GDD*, and *PTU* for each specific model were then averaged. The mean *ND*, *GDD*, or *PTU* for each model was used to predict when a growth stage should be reached for each of the 19 data sets, and the observed and simulated dates were then compared by calculating the root mean square error (*RMSE*):

$$RMSE=\left[\frac{\sum_{i=1}^{n}[OBS_i-SIM_i]^2}{n}\right]^{1/2} \tag{3}$$

where i is the n^{th} data set of 19 data sets. The less the simulated deviates from the observed, the smaller the *RMSE*. The sum of the residuals (*SRES*) and the sum of the absolute residuals (*SARES*) were calculated (Heuer et al., 1978) to infer the tendency of a model to consistently under- or over-estimate the dates of predicted growth stages. Clearly, the *RMSE* does not provide an independent validation of the models nor is it intended to; its value lies in giving an indication of the variability of the 19 data sets for each particular model. By including *SRES* and *SARES*, additional information is added over simply calculating the variance. The authors wished to obtain as large a sample size for calculating the *GDD*, *PTU*, and *ND* for each interval in order to best estimate the numbers for a variety of base temperatures and upper thresholds.

RESULTS AND DISCUSSION

Mean estimates for the best number of calendar days (*ND*), growing degree-days (*GDD*), and photothermal units (*PTU*) models for each growth stage are presented in Table 2. Generally, the lower the base temperature for a given model, the lower the root mean square error (*RMSE*) when beginning accumulation from seeding (S), emergence (E), or 1 January, with the $-2\,^{\circ}$C base temperature frequently having the lowest *RMSE*. Deviation from this generality occurred for dormancy end (DE), kernel in hard dough (KD), and maturity (M) where higher base temperatures occasionally had the lowest *RMSE* when accumulating *GDD* or *PTU* from seeding, emergence, or the previous growth stage. Higher base temperatures (often 3–6 °C) are frequently reported as best in the literature, with the optimum varying with the growth stage and tending to increase as M is approached (e.g., Nuttonson, 1955; Wang, 1960;

TABLE 2

Each model ranked from lowest to highest root mean square error (*RMSE*) for each growth stage interval

Model Interval	*ND*	GY20		GY25		GY30		GN		PY20		PY25		PY30		PN	
		base	*GDD*	base	*GDD*	base	*GDD*	base	*GDD*	base	*PTU*	base	*PTU*	base	*PTU*	base	*PTU*
S–E	8.3	−2	157	−2	161	0	145	0	145	−2	1931	−2	1982	−2	1986	−2	1986
		0*	140	0*	144	−2	161	−2	161	0	1727	0*	1779	0*	1783	0*	1783
		1*	132	1*	136	1	136	1	136	1*	1626	1*	1677	1*	1681	1*	1681
S–TI	20.2	−2	364	−2	370	−2	371	−2	371	−2	4391	−2	4473	−2	4477	−2	4477
		0	323	0	330	0	330	0	330	0	3906	0	3988	0	3991	0	3991
		1	303	1	310	1	310	1	310	1	3663	1	3745	1	3749	1	3749
E–TI	12.9	−2	225	−2	228	−2	228	−2	228	−2	2685	−2	2718	−2	2718	−2	2718
		0	200	1	189	1	189	1	189	0	2378	0	2412	0	2412	0	2412
		1	187	0	202	0	202	0	202	1	2225	1	2259	1	2259	1	2259
S–DE	174.6	−2	1072	9	250	9	250	9	250	−2	11986	−2	12071	−2	12075	−2	12075
		9	243	2	682	2	682	2	682	9	2851	9	2937	9	2940	9	2940
		7	339	7	346	7	346	7	346	0	9683	0	9768	0	9772	0	9772
E–DE	167.3	−2	933	−2	936	−2	936	−2	936	2	6338	2	6375	2	6375	2	6375
		9	184	9	187	9	187	9	187	9	2125	9	2162	9	2162	9	2162
		7	266	4	431	4	431	4	431	1	7203	1	7241	1	7241	1	7241
JAN–DE	67.7	4	18	4	18	4	18	4	18	3	291	3	291	3	291	3	291
		3	26	3	26	3	26	3	26	4	197	4	197	4	197	4	197
		2	38	2	38	2	38	2	38	0	766	0	766	0	766	0	766
TI–DE	154.5	−2	724	−2	724	−2	724	−2	724	0	5937	0	5940	0	5940	0	5940
		0	548	0	549	0	549	0	549	−2	7778	−2	7782	−2	7782	−2	7782
		1	472	1	472	1	472	1	472	1	5129	1	5132	1	5132	1	5132
S–J	227.6	−2	1570	−2	1577	−2	1578	−2	1578	−2	18442	−2	18536	−2	18540	−2	18540
		0	1258	0	1265	0	1266	0	1266	0	14877	0	14791	0	14975	0	14975
		1	1115	1	1123	1	1123	1	1123	1	13242	1	13335	1	13339	1	13339
E–J	220.3	−2	1431	−2	1435	−2	1435	−2	1435	−2	16733	−2	16779	−2	16779	−2	16779
		0	1134	0	1137	0	1137	0	1137	0	13347	0	13393	0	13393	0	13393
		1	999	1	1003	1	1003	1	1003	1	11801	1	11847	1	11847	1	11847
JAN–J	120.7	−2	614	−2	614	−2	614	−2	614	−2	7716	−2	7724	−2	7724	−2	7724
		0	470	0	471	0	471	0	471	0	5970	0	5978	0	5978	0	5978
		1	406	1	407	1	407	1	407	1	5181	1	5190	1	5190	1	5190

DE-J	54.0	−2	505	−2	506	−2	506	−2	506	−2	6539	−2	6548	−2	6548	−2	6548
		0	405	0	406	0	406	0	406	0	5255	0	5264	0	5264	0	5264
		1	358	1	358	1	358	1	358	1	4648	1	4657	1	4657	1	4657
TI-J	215.2	−2	1222	−2	1223	−2	1223	−2	1223	−2	14234	−2	14246	−2	14246	−2	14246
		0	948	0	949	0	949	0	949	0	11131	0	11143	0	11143	0	11143
		1	825	1	826	1	826	1	826	1	9726	1	9783	1	9738	1	9738
S-H	259.1	−2	2054	−2	2068	−2	2068	−2	2068	−2	25413	−2	25590	−2	25598	−2	25598
		0	1679	0	1692	0	1693	0	1693	0	20945	0	21222	0	21130	0	21130
		1	1506	1	1519	1	1520	1	1520	1	18860	1	19038	1	19045	1	19045
E-H	251.8	−2	1916	−2	1925	−2	1926	−2	1926	−2	23703	−2	23833	−2	23837	−2	23837
		0	1555	0	1565	0	1566	0	1566	0	19415	0	19544	0	19548	0	19548
		1	1389	1	1398	1	1399	1	1399	1	17420	1	17549	1	17553	1	17553
JAN-H	152.2	−2	1098	−2	1105	−2	1105	−2	1105	−2	14689	−2	14781	−2	14785	−2	14785
		0	892	0	898	0	899	0	899	0	12040	0	12132	0	12136	0	12136
		1	795	1	803	1	803	1	803	1	10802	1	10894	1	10898	1	10898
J-H	32.5	3	338	2	375	2	376	2	376	1	5779	0	6326	0	6330	0	6330
		0	434	0	440	3	344	3	344	−2*	7173	1	5863	1	5867	1	5867
		1	402	3	343	1	408	1	408	0*	6242	−2*	7256	−2	7260	−2	7260
S-KM	269.8	−2	2263	−2	2285	−2	2286	−2	2286	−2	28494	−2	28811	−2	28826	−2	28826
		0	1866	0	1889	0	1890	0	1890	0	23708	0	24026	0	24041	0	24041
		4	1192	3	1368	2	1532	2	1532	1	21464	1	21782	1	21797	1	21797
E-KM	262.5	−2	2124	−2	2143	−2	2144	−2	2144	−2	26784	−2	27054	−2	27065	−2	27065
		4	1098	4	1116	3	1263	3	1263	0	22178	0	22447	0	22459	0	22459
		5	962	5	981	0	1762	0	1762	3	16054	3	16323	2	18263	2	18263
JAN-KM	162.9	−2	1306	−2	1322	−2	1323	−2	1323	−2	17765	−2	17997	−2	18008	−2	18008
		0	1078	0	1094	0	1095	0	1095	0	14798	0	15030	0	15042	0	15042
		1	972	1	988	1	989	1	989	1	13401	1	13633	1	13645	1	13645
H-KM	11.7	−2	227	−2	237	−2	237	−2	237	2	2662	−2	3498	−2	3506	−2	3506
		0	203	1	201	0*	214	0*	214	−2	3356	0	3151	4	2464	4	2464
		1	192	0	213	1*	202	1*	202	1	2835	3	2630	0*	3158	0*	3158
S-KD	286.2	−2	2668	−2	2732	−2	2744	−2	2745	−2*	34240	−2	35170	−2	35353	−2	35362
		5	1310	3	1711	0	2808	0	2308	4*	19445	2	24883	0	30015	1	27496
		7	1013	2	1896	1	2103	1	2103	0	28902	4	20375	2	25066	2	25075

TABLE 2 (*continued*)

Each model ranked from lowest to highest root mean square error (*RMSE*) for each growth stage interval

Model Interval	*ND*	GY20		GY25		GY30		GN		PY20		PY25		PY30		PN	
		base	*GDD*	base	*GDD*	base	*GDD*	base	*GDD*	base	*PTU*	base	*PTU*	base	*PTU*	base	*PTU*
E–KD	279.5	9	700	3	1611	5	1300	5	1300	5	16361	2	23564	−2	33697	−2	33707
		7	944	5	1288	4	1456	4	1456	7	12705	4	19222	4	19399	4	19409
		5	1228	9	760	2	1801	−2	2611	−2	32648	−2	33520	5	17410	5	17420
JAN–KD	177.9	−2	1654	−2	1710	−2	1722	−2	1723	−2	22878	−2	23704	−2	23881	−2	23891
		0	1394	1	1326	0	1461	0	1462	0	19435	0	20260	0	20438	0	20447
		1	1271	0	1449	1	1338	1*	1339	2	16215	2	17040	1	18799	1	18809
KM–KD	18.1	7	219	9	224	5	307	5	308	7	3268	4	4692	7	4050	−2	6489
		−2*	382	4	314	0	398	7	272	2*	4618	−2*	6312	−2	6480	9	3520
		0*	345	5	296	3*	344	4	326	3*	4348	0*	5772	9	3511	1*	5679
S–M	293.8	9	821	9	905	9	922	9	923	7	14773	7	16011	5	20258	5	20267
		7	1088	7	1172	7	1189	7	1190	9	11246	9	12484	7	16263	4	22419
		5	1395	5	1479	5	1496	5	1497	5	18768	5	20006	4	22409	7	16272
E–M	286.5	9	762	9	843	9	860	9	860	9	10520	7	15059	5	19123	5	19133
		7	1015	7	1096	7	1112	7	1113	7	13869	9	11710	7	15308	7	15317
		4	1467	4	1547	4	1564	4	1565	4	19747	3	23113	4	21185	−2	35892
JAN–M	186.9	−2	1820	−2	1897	−2	1914	−2	1915	−2	25431	−2	26587	−2	26835	−2	26844
		0	1544	0	1622	0	1638	1	1509	0	21748	0	22903	0	23152	0	23161
		1	1414	3	1248	2	1383	2	1384	2	18300	2	19456	1	21397	1	21406
KD–M	8.9	9	96	9	127	9	135	9	135	7*	1697	9	1886	9	2004	9	2006
		0*	176	−2*	225	7	153	7	153	9*	1431	7	2151	2*	2934	2*	2936
		1*	168	0*	207	3	188	3	188	−2†	2892	−2*	3346	3*	2801	3*	2803
H–M	34.7	9	348	7	490	4	614	3	650	9	5177	1	10492	9	6487	9	6496
		3	562	1	705	1	721	9	436	7	6236	2*	9960	0	11268	−2	12342
		5	490	9	419	9	436	−2	829	5	7299	3*	9428	1	10736	2	10214

* or †Base temperatures had the same RMSE, with equal sum of the residuals and sum of the absolute residuals.

Iwata, 1975; Angus et al., 1981; Del Pozo et al., 1987). However, few studies have tried negative base temperatures.

The best model for predicting a particular growth stage varied (Table 3): for the stages E, tiller initiation (TI), DE, and jointing (J), *ND* had the lowest *RMSE* of all models; from heading (H) through M, *PTU* models had the lowest *RMSE*. In all cases except DE, the best *GDD* or *PTU* models used a −2°C base temperature. Generally, *GDD* and *PTU* models beginning accumulation 1 January had the lowest *RMSE*. Only for H and KD growth stages, did beginning accumulation at emergence and sowing, respectively, result in models with the lowest *RMSE*: upper limits have not commonly been used in previous efforts. As M was approached, the 25°C upper threshold tended to be better than 20°C. Little difference was found between 25 and 30°C upper thresholds, as expected, since the average daily temperature rarely exceeds 25°C. Usually, for models with low *RMSE*, resetting the average daily temperature, if below the base temperature or above an upper threshold, increased the predictive power of the model over those models where the temperature was not reset. This is probably due to temperatures exceeding thresholds contributing less to development, if indeed the excess temperatures do not alter the development rate.

Heuer et al. (1978), Neghassi (1974), and Robertson (1968) support the superiority of the *ND* model to heat unit models for early growth stages. Robertson (1968) found no effect of photoperiod on the period from S to E as expected, because light should have a minimal impact on buried seeds and their germination and initial growth. Part of the explanation for the *ND* model estimating E better than *GDD* or *PTU* models was that the time interval from S to E is very short (mean = 8.3 days) with a relatively small range in calendar days about the mean. There are limits on the maximum rate of germination and growth regardless of conditions, and the shortest interval observed was six days. Given the observed truncated and skewed distribution about the mean number of days to E, the tendency to predict E early using the *ND* model is restricted, thus reducing the *RMSE* encountered. If this is true, the sum of the residuals should be a negative number as was found. Also, since seeds were planted in sufficient soil water for germination and seedling growth, the environmental variability for S to E was less than for other growth stages.

Few studies were found in the literature which attempted to predict winter wheat TI and DE. Perhaps if more attempts to predict these growth stages had been made, more instances of the *ND* model out-performing *GDD* and *PTU* models might have been found. Such might be the case for DE because accumulation of *GDD* or *PTU* from either S or E, as is normally done, will result in some data sets predicting DE during fall. Using the mean observed number of days to DE will rarely, if ever, result in predicting DE in the fall unless an early planting date is used; thus, the *ND* model will usually predict DE better

TABLE 3

Models with the lowest root mean square errors (*RMSE*) for predicting when a specific growth stage will be reached. "STAGES" represents using either the *GDD* or *PTU* model with the best *RMSE* for each interval using successive growth stages. "S", "E", or "J" following the model type indicates whether the date for beginning accumulation was seeding, emergence, or 1 January, respectively

Stage	Ranking	Model	*RMSE*
Emergence	1	ND,S	2.197
	2	STAGES,S	2.362
		PY20(−2),S	2.362
	3	GY20(−2),S	2.373
Tiller initiation	1	ND,S	3.243
	2	STAGES,E	3.441
		GY25(−2),E	3.441
		GY30(−2),E	3.441
		GN(−2),E	3.441
Dormancy end	1	ND,S	9.456
	2	PY20(3),J	13.097
		PY25(3),J	13.097
		PY30(3),J	13.097
Jointing	1	ND,S	10.062
	2	PY20(−2),J	11.388
		PY25(−2),J	11.388
		PY30(−2),J	11.388
Heading	1	PY25(−2),E	7.790
	2	STAGES (exclude DE),E	7.820
	3	PY20(−2),E	7.867
	4	PY30(−2),E	7.931
		PN(−2),E	7.931
Kernel in milk	1	PY25(−2),J	6.728
	2	PY30(−2),J	6.740
		PN(−2),J	6.740
	3	PY20(−2),J	6.951
Kernel in hard dough	1	PN(−2),S	5.561
	2	PN(−2),J	5.691
	3	PY30(−2),S	5.731
Maturity	1	STAGES (exclude DE,KM,KD),J	7.391
		PY25(−2),J	7.391
	2	PY20(−2),J	7.511
	3	PY30(−2),J	7.567
		PN(−2),J	7.567

than the *GDD* and *PTU* models. Heuer et al. (1978) also encountered difficulty in predicting DE. The imprecision in the Feekes scale, especially for jointing, probably added substantially to the variation in all of the models for estimating jointing. As maturity was approached, the ability of the *ND* model to predict more accurately than the best *GDD* and *PTU* models was significantly reduced, thus agreeing with the literature (e.g. Bauer et al., 1984b). The overall results where the *PTU* models outperformed the *GDD* models also agrees well with earlier work (e.g. Bauer et al., 1984b).

Typically, *GDD* and *PTU* models begin accumulating from either seeding (S), emergence (E), or the beginning of the previous growth stage. The relative success in this study of using 1 January as the initial point demonstrates that models beginning at S or E do not sufficiently account for all the variation, especially for vernalization. If the plant can only develop to a specific stage during the fall, then additional accumulated heat or photothermal units are ineffective and result in added noise for all models that begin accumulation at S or E. If accumulation begins 1 January, this is a technique to indirectly correct for not incorporating vernalization explicitly. However, as latitude decreases (i.e. winters become less severe), this indirect correction will probably become less effective.

Not only the best model for predicting a growth stage varied, but how well the best model predicted a particular growth stage varied considerably for various growth stages as reflected in the *RMSE* values (Tables 2, 4). Emergence (E) and tiller initiation (TI) had the lowest *RMSE*, but this is not surprising given the short time span from seeding to these stages. The accuracy of predicting growth stages past jointing (J) increased as maturity (M) was approached. All models had a slight tendency to estimate the growth stage late, but this tendency was not pronounced (the mean was less than a day). The reason for this is that all of the daily *GDD* or *PTU* will be included in the sum for when the growth stage will be reached, even though the growth stage was reached at variable times during the day. When requiring a certain number of *GDD* or *PTU* to reach a growth stage, this number will be biased high, and therefore, the predicted day will be slightly later than the observed. This also explains why using the best model for successive growth stages does not always outperform models starting accumulation from 1 January or E. As more intermediate growth stages are involved, the error compounds.

Although the effect of various environmental conditions and cultural practices on phenology has often been studied, sensitivity of simple phenology models to environmental conditions and cultural practices has infrequently been examined. Simple linear least-squares regressions, Mann-Whitney tests, and other tests were used to examine the sensitivity of the best *GDD*, *PTU*, and *ND* model types for available soil water, fertilizer, planting date, row spacing/rotation, and cultivar. Assumptions of the parametric tests may not have been satisfied, probably resulting in a Type II error where significance was not detected ($\alpha = 0.05$).

TABLE 4

Using the *GDD* or *PTU* model with the lowest root mean square error for estimating a specific growth stage to show the difference between the observed day that a growth stage was reached minus the simulated day for each data set. Refer to Table 3 for which model was used for each growth stage

Data sets	E	TI	DE	J	H	KM	KD	M	Mean not including DE (±1 *SE*)	Mean including DE (±1 *SE*)
Akron										
1977-78	−1	−1	−10	8	0	−8	−4	−2	−2.2(1.93)	−1.1(1.83)
1978-79	0	0	−21	−6	−8	−7		−9	−7.3(2.67)	−5.0(1.63)
1979-80	−3	5	21	−16	−7	−6	−5	−4	−1.9(3.85)	−5.1(2.34)
1980-81	0	3	5	4	−5	7	2	16	4.0(2.14)	3.9(2.46)
Mean (*SE*)									−1.8(2.31)	−1.8(1.73)
Medford										
1977-78	−3	−2	−15	4	4	5	−3	−4	−1.8(2.30)	0.1(1.50)
1978-79	2	0	4	5	8	4		2	3.6(0.97)	3.5(1.15)
Mean (*SE*)									0.9(2.70)	1.8(1.70)
Albin										
1977-78	−3	−3	−11	−10	3	−13	0	−7	−5.5(2.00)	−4.7(2.12)
1978-79	6	2	−5	−2	3	3		−4	0.4(1.56)	1.3(1.50)
1979-80	−1	0	10	−8	−13	−3		−6	−3.0(2.74)	−5.2(2.00)
Mean (*SE*)									−2.7(1.71)	−2.9(1.41)
Paxton										
1977-78	−3	−4	−12	−5	−7	−6		0	−5.3(1.41)	−4.2(1.01)
1978-79	3	−1	−5	−3	−4	1	−4	−2	−1.9(0.97)	−1.4(1.00)
1979-80	1	−6	5	−18	−14	−4	−12	−6	−6.8(2.72)	−8.4(2.47)
Mean (*SE*)									−4.7(1.45)	−4.7(2.03)

Mankato										
1977-78	−3	−9	−10	19	7	3	8	20	4.4(4.05)	6.4(4.03)
1978-79	−2	0	−5	18	7	17		9	6.3(3.43)	8.2(3.40)
Mean (*SE*)									5.4(2.31)	7.3(0.90)
Tribune										
1977-78	−1	1	−12	21	14	5	8	2	4.8(3.52)	7.1(3.00)
1978-79	0	−1	11	1	11	0	5	−3	3.0(1.92)	1.9(1.78)
1979-80	0	0	19	−17	−8	−7	−5	−5	−2.9(3.65)	−6.0(2.18)
Mean (*SE*)									1.6(2.33)	1.0(3.81)
Garden City										
1977-78	−2	6	−12	−3	−2	−3	1	0	−1.9(1.79)	−0.4(1.21)
1979-80	0	1	26	−10	−2	0	3	1	2.4(3.65)	−1.0(1.60)
Mean (*SE*)									0.2(2.15)	−0.7(0.30)
Mean	−0.5	−0.5	−0.9	−0.9	−0.5	−0.6	−0.5	−0.1		
±1 SE	0.54	3.50	3.08	2.67	1.83	1.58	1.60	1.74		

One conclusion that could be drawn from the regressions was that even when significant slopes were found ($\alpha = 0.05$), the r^2 was quite low (always less than 0.50, and typically about 0.30). This suggests that even when models showed sensitivity to the independent variable, little variation was explained by the independent variable when using this approach. Unless a better method of representing the effect of cultural practices and environmental conditions can be incorporated into these simple regression and phenological models, little value will be gained from incorporating cultural practices and environmental conditions (light and temperature excepted) into the models.

Variable results are encountered in the literature when examining the role of water stress on phenological development. Some studies report no relationship between water availability and phenological development of the main stem (e.g. Davidson and Campbell, 1983; Bauer et al., 1984b), while other studies suggest some relationship or that a relationship should exist (e.g. Wang, 1960; Hodges and Doraiswamy, 1979; Mor and Aggarwal, 1980; Doraiswamy and Thompson, 1982; Singh et al., 1984). Angus and Moncur (1977) reported a stronger response for tillers to water stress than the main stem. In predicting how water stress will affect development rates, the hypothesis could be postulated that mild to moderate stress would increase phenological development rate and extreme water stress would strongly reduce development (Heuer et al., 1978; Sionit, 1980). Water stress may alter development rate by several mechanisms which could include hormonal action, particularly by reducing cytokinin production by the roots when root growth slows due to the effects of increased water stress, by increasing plant temperature by stomatal closure, or by developmental modifications of the "normal" sequence.

For jointing (J) through maturity (M), a rough parabolic relationship (concave downward) between *GDD* and *PTU* with available soil water at seeding, available soil water at seeding plus precipitation from seeding to the growth stage, available soil water at dormancy end (DE), and available soil water at J was found. The shape of the parabola varied from J through M in that it became increasingly platykurtic. Although soil water availability is not directly related to plant water stress, these results suggest indirect support for the hypothesis on the role of plant water stress on phenological development rates. The mode of impact is assumed to be associated with mild plant water stress for dryland conditions. The parabolic nature of the data would explain why *GDD*, *PTU*, and *ND* models rarely show significance in linear regressions, and indicates the need for curvilinear regression.

The effect of planting date and fertilizer application at sowing was never noticed until DE, and then almost only for the *ND* model. In the case of planting date, for growth stages DE through M, these stages only occur after a certain point regardless of planting date. Therefore, as planting is delayed, the *ND* to the growth stage will normally be less and a significant regression slope would be expected.

Differences between row spacing and rotation could not be distinguished because only two row spacings and two rotations were used, and the same row spacing was used with the same rotation. The combined effect was significant differences among rotation/row spacing for all models for J, H, kernel in milk (KM), and M. The small sample size may be why KD was not significant. The biological explanation for the significant differences may be due to the effects of row spacing and rotation on available resources such as light, nutrients, and particularly water. For example, as row spacing increased from 18 to 30 cm and the rotation changed from continuous wheat to wheat-fallow, more available soil water was present. As water availability increases, the required *GDD* and *PTU* to reach a particular growth stage should also increase. This was the case in our study as more *GDD* and *PTU* were required for wider row spacing and wheat-fallow rotation.

Phenological differences among cultivars have been reported to exist (e.g. Nuttonson, 1955; Wang, 1960; Saini and Tandon, 1983; Bauer et al., 1984a; Singh et al., 1984; Klepper et al., 1985). Robertson (1968) found the greatest differences in *GDD* among cultivars for H rather than M. If the stages most sensitive to water stress are near J, as suggested by the parabolic shapes found as a function of available soil water, perhaps this explains why the largest variation among cultivars is found near H when using *GDD* and *PTU* models that do not account for water stress. Results showed that Scout 66 tended to develop slightly faster (less than 2 days for all growth stages combined) and Centurk slightly slower (less than 3 days) than the mean. For a large number of cultivars planted at Akron and Fort Collins, CO, there is seldom more than one week's difference in reaching specific growth stages (Smika and McMaster, unpublished data). Differences should be most pronounced for cultivars bred for other climatic or geographic regions or cultivars that are morphologically different.

CONCLUSIONS

Simple empirical models using *GDD*, *PTU*, and *ND* were calculated using a variety of base and upper threshold temperatures allowing comparisons of different methods used in the literature. The accuracy of these models varied considerably depending on the growth stage, site, year, environmental conditions, and cultural factors. Selection of the "best" model depends on the specific growth stage that is being estimated and generalizing to some "best" model for all stages is dangerous.

Several areas of improvement can be suggested to enhance *GDD* and *PTU* models. If estimates of crown temperature can be obtained, a more realistic affect of temperature on phenological development should be derived since meristematic tissue temperature is more important than air temperature. Previous attempts to more accurately calculate daily average temperatures such as by Heuer et al. (1978) by using simulated hourly values rather than daily maximum and minimum air temperature proved unsatisfactory mainly due to inaccurately predicted hourly air temperatures. With the development of better models (e.g. Parton and Logan, 1981), there appears to be need to repeat some of the earlier work. While temperature and photoperiod explain most of the variation in phenological development rates, it is not clear whether the response to temperature is linear as used in most models. If response to temperature is linear, then changing the base temperature and upper threshold for a given model should not affect the root mean square error. Data showed the optimum base temperature and upper threshold increased as maturity was approached, indirectly suggesting that for some growth stages response to temperature is not linear. Angus et al. (1981) also found non-linear temperature response for certain growth phases. Finally, without incorporating a number of environmental, genetic, and cultural factors into simple *GDD* and *PTU* models, these models will always be somewhat limited and erratic in their application and behavior. Particularly cultivar differences, planting date, and water stress relationships must be incorporated. Perhaps a multiple regression approach would be the simplest method, even though explanation of mechanisms involved would be lacking.

ACKNOWLEDGEMENTS

The authors express their appreciation to W.O. Willis for his generous donation of both his time and support staff. Without his cooperation and input this project could never have proceeded to this point. Also, A. Bauer, E.T. Kanemasu, J.A. Morgan, R.W. Rickman, and W.W. Wilhelm have substantially aided this project by reviewing this manuscript, to which the authors remain responsible for any remaining errors.

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