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INTRODUCTION

The concept of growing degree days (GDD) originated with observations by Reamur (1735) that plant development is more closely related to the temperature accumulated to a given stage than with time alone. It was not until nearly 200 years later, however, that Merriam (1894), Livingston (1916) and Klages (1942) began to use temperature accumulations in plant distribution studies and in crop geography.

In the early 1950's, a system involving growing degree days became widely used in the canning industry to schedule plantings and thus control time of harvest of rapidly maturing vegetables. This system provided a more precise control of both quantity and maturity of produce delivered for processing. It had a profound effect on processing efficiency and the cost and quality of canned vegetables, particularly peas and sweet corn.

Tables and maps of growing degree days are now available for many states and for larger regions (Baker and Strub, 1965; Neild *et al.*, 1967; Dethier and Vittum, 1967, and Shaw, 1975). These data are useful for evaluating climate relative to crop and variety adaptability and for crop scheduling.

Breeders and field corn seed producers use GDD to predict time of tasseling for controlling pollination. They are also interested in classifying hybrids on the basis of their GDD requirements. Gilmore and Rodgers (1958), Brown (1963), Newman (1971), Aspiazu and Shaw (1972), Cross and Zuber (1973), and Mederski *et al.* (1973) have studied relationships between different methods of computing GDD and corn maturity. The (50/86) method[2], first proposed by Gilmore and Rodgers (1958) is slightly more precise than other methods, but the coefficients of variation among other methods using a base temperature of 50°F were small. The interest in most of these studies was limited to only two stages of crop development—reproduction and maturity.

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[2]The 50/86 method does not accumulate maximum temperatures above 86°F or minimums below 50°F in calculating the daily average temperature.

This study concerns GDD requirement for the series of consecutive phenological stages of field corn (*Zea mays* L.) and grain sorghum (*Sorghum bicolor* (L.) Moench) from emergence to physiological maturity. Such data are important for crop management decisions throughout the growing season.

MATERIALS AND METHODS

Three field corn hybrids, A619 x A632, Neb 611, and N28 x Mo17, were planted at approximate 7-day intervals between April 22 and June 25 at Mead, Nebraska in 1975 and 1976. Three grain sorghum hybrids, NB 505, RS 626, and RS 671 were also planted on this same schedule, except for the first planting. These hybrids represent the range of maturities commonly used in Nebraska. The nine corn and eight grain sorghum planting dates represent the extremes as well as the most active times of planting.

Phenological observations were made weekly for all varieties and planting dates using photographs and descriptions of the 10 successive development stages of field corn (Hanway, 1971), and 9 stages of

Table 1. Growing degree days for different development stages and hybrids of field corn and grain sorghum.

Stage of development	Stage number	Field Corn		
		A619 X A632	NEB 611	N28X Mo17
Two leaves fully emerged	0.5	193	213	213
Four leaves fully emerged	1.0	312	345	349
Six leaves fully emerged	1.5	431	476	484
Eight leaf fully emerged	2.0	550	608	619
Tenth leaf fully emerged	2.5	669	739	754
Twelfth leaf fully emerged	3.0	788	871	889
Fourteenth leaf fully emerged	3.5	907	1003	1024
Sixteenth leaf fully emerged	4.0	1026	1134	1159
Silks emerging, anthesis	5.0	1264	1397	1430
Kernels in blister stage	6.0	1502	1661	1700
Kernels in dough stage	7.0	1740	1924	1970
Kernels beginning to dent	8.0	1979	2187	2240
Kernels fully dented	9.0	2217	2450	2511
Physiological maturity	10.0	2455	2713	2781
		Grain sorghum		
Stage of development		NB505	RS626	RS671
Emergence-Coleoptile visible	0.0	–	–	–
Collar of 3rd leaf visible	1.0	254	264	294
Collar of 5th leaf visible	2.0	498	527	580
Growing point differentiated	3.0	741	790	866
Final leaf visible in whorl	4.0	985	1053	1151
Boot stage	5.0	1229	1317	1437
Half bloom	6.0	1473	1580	1723
Kernels in soft dough	7.0	1717	1843	2008
Kernels hard	8.0	1961	2106	2294
Physiological maturity	9.0	2205	2369	2580

grain sorghum (Vanderlip, 1972). These stages are shown in Table 1. The numerical value for the observed stage of development was recorded. When necessary, decimal fractions were used for interpolations between stages. Accumulated growing degree days above 50°F, $GDD = \frac{(Max + Min)}{2} - 50$ were determined for the phenological stage observations for all hybrids and planting dates.

Many researchers view the (50/86) method as being biologically more realistic and slightly more precise than the simpler base 50 method. However, the base 50 method was used in this study because the available GDD normals for Nebraska and other areas as well are calculated in this manner. Base 50 GDD normals can be computed from daily mean temperatures and also monthly average temperatures (Holmes and Robertson, 1959 and Neild and Greig, 1971), whereas the (50/86) method requires daily maximum-minimum temperatures for all days during all the years for which normals are developed. Such data are not readily available for many locations. Linear regression was used to study the relationships between GDD from planting and different stages of crop development for the three corn and three grain sorghum varieties.

RESULTS

Statistics of the analysis for these hybrids are listed in Table 2. The analysis of composited data as well as the specific years are shown separately. The coefficients of determination (r^2) show close correspondence between time, GDD, and crop development. For example, in 1975, days from planting explained 94-97% of the variation in crop development. GDD accounted for 98% of the variation in crop development.

The standard errors of estimate (S.E.) showed GDD to be the more accurate parameter for predicting crop development. In the composited data, the standard errors in estimating stage of development of the different corn hybrids using days from planting ranged from .60 to .83. The standard errors of estimates using GDD ranged from .34 to .40. The S.E. for the different grain sorghum hybrids with days from planting as the predictor ranged from .49 to .64, compared with .30 to .32 using GDD. This agrees with numerous studies which show GDD to be the best predictor.

Regression coefficients (b) for GDD vs development stage for the different corn and sorghum hybrids in 1975 and 1976 were very close. In fact, regression coefficients for corn hybrids were identical for both years. Regression coefficients for early and mid season grain sorghum hybrids differed by only .0001 stage units between years. Coefficients for the late variety were identical. The regression coefficients showed that slower rates of development occur for later maturing hybrids. For example, the composited data showed that the ear-

Table 2. **Coefficients of determination (r^2), intercepts (a), regression coefficients (b) and standard errors (SE) between days and GDD from planting and stage and development for corn and grain sorghum hybrids.**

	Days					GDD			
	n	r^2	a	b	SE	r^2	a	b	SE
1975									
Field corn									
A619 X A632	128	.95	−.74	.0966	.69	.98	−.33	.0042	.40
Neb 611	134	.95	−.62	.0896	.68	.98	−.29	.0038	.44
N28 X Mo17	136	.95	−.58	.0862	.64	.97	−.26	.0037	.47
Grain Sorghum									
NB 505	100	.95	−.47	.1000	.66	.98	−.16	.0041	.37
RS 626	107	.96	−.33	.0916	.59	.98	−.06	.0038	.36
RS 671	112	.96	−.27	.0856	.51	.98	−.01	.0035	.37
1976									
Field Corn									
A619 X A632	88	.92	−.61	.0898	.92	.99	−.27	.0042	.23
Neb 611	109	.94	−.65	.0835	.75	.99	−.34	.0038	.28
N28 X Mo17	109	.97	−.68	.0843	.51	.99	−.33	.0037	.30
Grain sorghum									
NB 505	97	.96	−.24	.0910	.57	.99	−.09	.0040	.20
RS 626	103	.97	−.24	.0845	.53	.99	−.07	.0037	.22
RS 671	105	.97	−.24	.0800	.41	.99	−.08	.0035	.24
Composited Data									
Field corn									
A619 X A632	216	.94	−.66	.0947	.83	.99	−.31	.0042	.34
Neb 611	243	.94	−.60	.0860	.74	.99	−.31	.0038	.38
N28 X Mo17	245	.96	−.62	.0851	.60	.98	−.29	.0037	.40
Grain Sorghum									
NB505	197	.95	−.33	.0948	.64	.99	−.04	.0041	.31
RS 626	210	.96	−.27	.0876	.59	.99	−.004	.0038	.30
RS 671	217	.97	−.24	.0825	.49	.99	−.03	.0035	.32

liest corn hybrid, A619 x A632, develops toward maturity at a rate of .0042 stage units per GDD, compared with .0038 and .0037 stage units respectively for Neb 611 and N28 x Mo17. A similar pattern can be seen for the grain sorghum hybrids, NB 505, RS 626, and RS 671, which are progressively later in maturity. The rate of development for field corn and grain sorghum hybrids of different maturities were similar. Field corn hybrid A619 x A632, and grain sorghum hybrid NB 505, had development rates of .0042 and .0041 respectively; Neb 611 and RS 626 were both .0038, while N28 x Mo17 and RS 671 were .0037 and .0035, respectively.

A comparison of days and GDD vs development stage of the early corn hybrid, A619 x A632, for the 1975 season in Figures 1 and 2, illustrates the much closer relationship for GDD. The standard error for stage, (Y) in relation to the different (X) variables, days and GDD from planting, are respectively .69 and .40. The standard error of these (X) variables in relation to stage are 7 days and 80 GDD, respec-

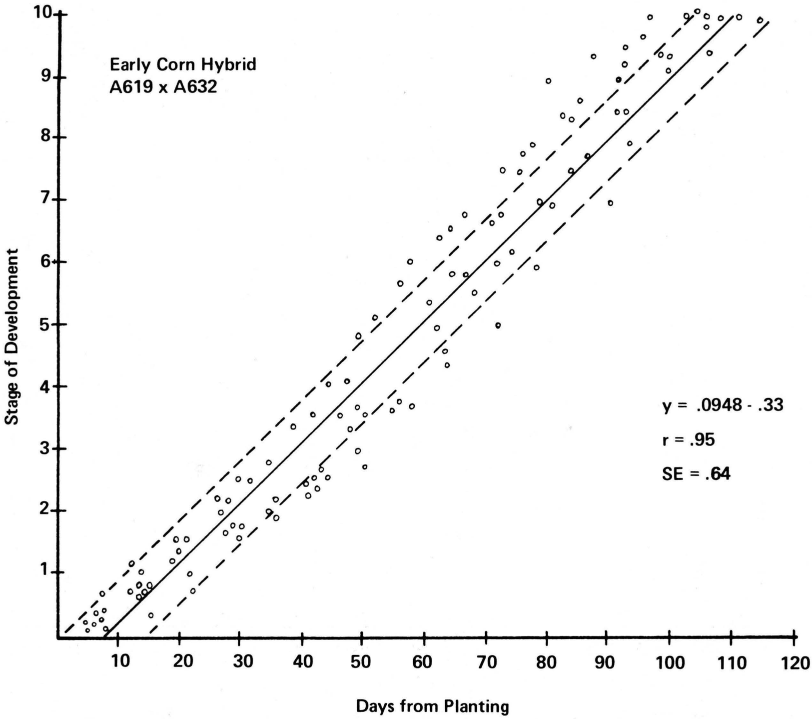

Figure 1. Relationship between days from planting and corn development.

tively. These values are the horizontal distance between the dashed (S.E.) and solid regression line. There normally are 28 GDD per day at Mead during the corn tasseling period. The 80 GDD error during tasseling is therefore equivalent to less than 3 days, ($80 \div 28 = 2.9$), compared to 7 days when time alone is used as the predictor.

Regression equations based on statistics in Table 2 were used to calculate the GDD requirements for the different development stages of the three field corn and grain sorghum hybrids. These data are presented in Table 1. Some interesting comparisons can be made. For example, the difference in GDD requirements between varieties increases with crop development. All three corn varieties reached stage 0.5 (two leaves), about 200 GDD from planting. The GDD for A619 x A632, Neb 611, and N28 x Mo17 were respectively 1264, 1397, and 1430 for stage 5.0 (reproduction), and 2217, 2450, and 2511 at stage 9.0 (fully dented).

Grain sorghum requires more GDD to reach the reproductive stage than field corn, but fewer GDD for physiological maturity. For example, the early grain sorghum hybrid, NB 505, required 1473 GDD to stage 6.0 (reproduction), and 2205 to stage 9.0 (physiological

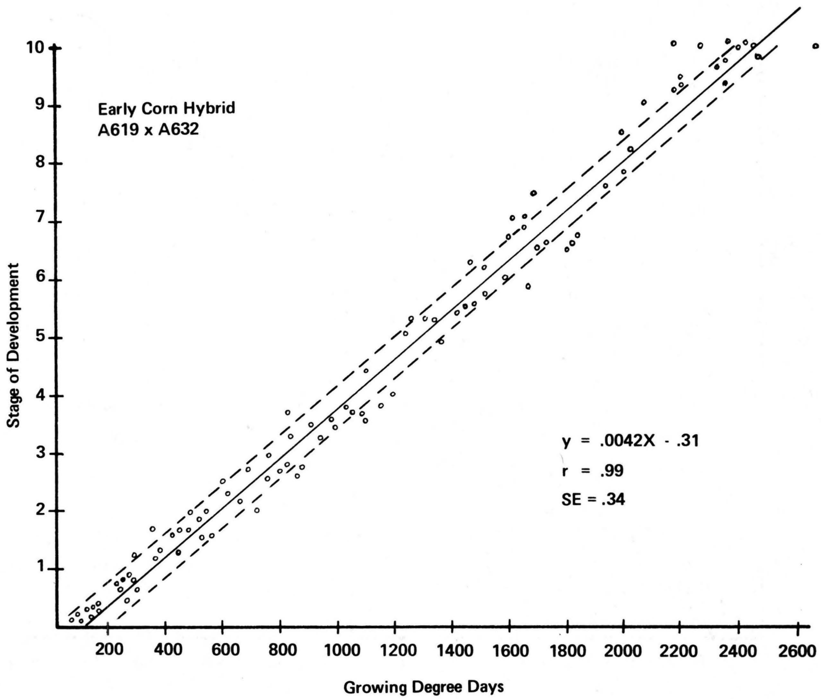

Figure 2. Relationship between growing degree days and corn development.

maturity). The early field corn hybrid, A619 x A632, required only 1264 GDD to reproduction, but 2455 GDD to physiological maturity. Similar comparisons may be made with other genotypes of these crops.

APPLICATIONS

The following applications are based upon the GDD requirements for the different development stages of the hybrids in Table 1 and GDD normals for different locations in Nebraska.

1. Expected response of a crop hybrid at different locations. There is a definite relationship between elevation, length of freeze-free season and growing season temperature from east to west across Nebraska. The elevations of Pawnee City (southeast), Gothenburg (central), and Mitchell (west), are 1175, 2565, and 4080 feet above sea level, respectively. The freeze-free season averages 168, 150, and 139 days, respectively. The effect of differences in growing season temperatures on grain sorghum hybrid RS 626 planted on May 5, as measured by GDD normals at these locations, is shown in Figure 3.

The hybrid would be expected to reach stage 1 (collar of third leaf visible) on 5/24 at Pawnee City, the warmest location; 5/31 at Gothenburg, but not until 6/9 at Mitchell where the elevation is the highest

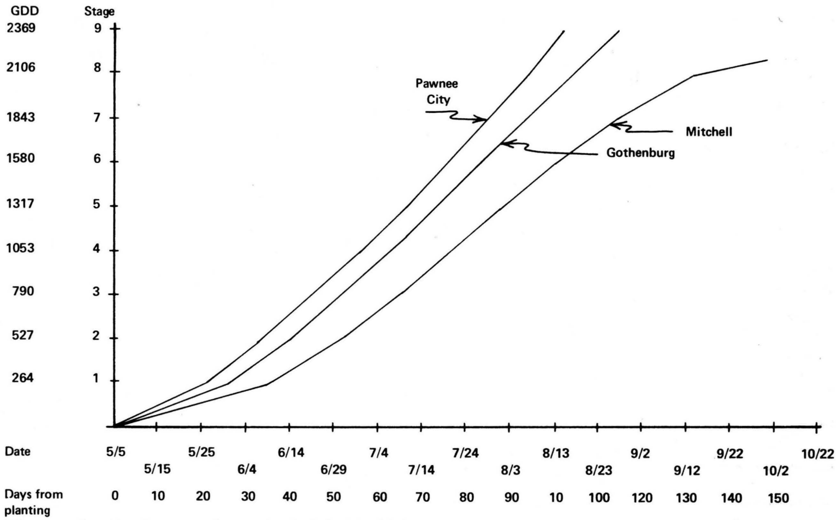

Figure 3.· Grain sorghum hybrid RS 626 planted May 5 at different locations.

and temperature the coolest. The expected times of half bloom (stage 6) at these locations are 7/19, 7/27, and 8/31 or 75, 83, and 100 days from planting. The hybrid would reach physiological maturity about 8/15 or 102 days from planting at Pawnee City and 8/27 or 114 days from planting at Gothenburg. The season is too cool and short for this hybrid to mature at Mitchell. There are only enough GDD for RS 626 to reach stage 8.2 (hard dough) before the first fall freeze at Mitchell.

2. *Expected response of different hybrids planted the same date.* Figure 4 shows the expected response of grain sorghum hybrids NB 505, RS 626 and RS 671 planted May 25 at Gothenburg in central Nebraska. These hybrids show similar response to temperature during the early stages, but differences in development become greater as the season progresses.

All hybrids reach stage 1 between 6/10 and 6/12 or 16 to 18 days from planting. The earliest hybrid, NB 505, would reach the boot stage (5) July 22 or 58 days from planting. This compares with 7/31 or 67 days for RS 671, the late variety. NB 505 would reach physiological maturity 8/31 or 98 days from planting; RS 626 on 9/6 or in 104 days, and RS 671 on 9/22 or 120 days from planting.

Because of different rates of development, hybrids from the same planting date progress through the later stages of development under different temperature regimes. For example, NB 505 advances from stage 8 to 9 in 11 days compared with 18 days for RS 671. About half of this difference in days between these two hybrids results from differences in rate of development. The other half results from the cooler temperature that prevails between these stages for the later hybrid.

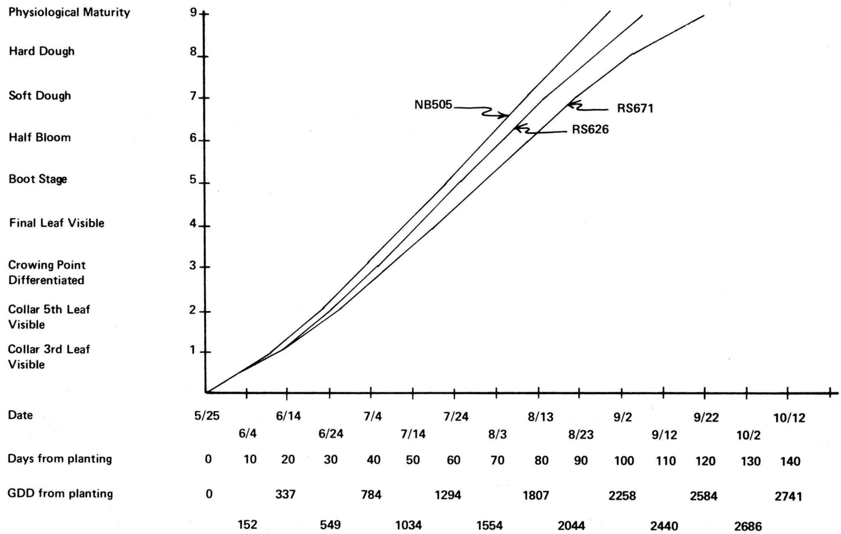

Figure 4. Grain sorghum hybrids NB505, RS 626 and RS 671 planted May 25 at Gothenburg.

3. Expected response of a hybrid to different planting dates. Figure 5 illustrates the expected response of grain sorghum hybrid RS 671, planted 5/5, 5/25, and 6/14. Differences in the time required for different plantings to reach similar stages of development can be seen. For example, the planting on 5/5 would reach stage 1 on 5/31 or 26 days from planting, compared with only 14 days when planted on June 14. The GDD are the same, 300, in both instances. The expected date for half bloom (stage 6) would be 8/2, 8/10, and 8/24 or in 89, 77, and 71 days, respectively, for plantings on May 5, May 25 and June 14. The May 5 planting would reach physiological maturity in 127 days. The May 25 planting would mature in 130 days. There would not be sufficient GDD for RS 671 to reach physiological maturity if planted as late as 6/14. It could only be expected to reach stage 8.3 if planted this late.

4. Predicting stage of development at a future date. Assume that field corn hybrid Neb 611, planted 5/15 at Gothenburg in central Nebraska, has accumulated 1150 GDD by 7/14. Substituting this GDD value for X in regression formula for this variety, ($Y = .0038X - .31$) would predict development at stage 4 (16 leaves). If normal temperatures (76°F) prevail, the hybrid would be expected to be at stage 4.75 in seven days.

Calculation:

1. GDD per day on July 14 $(76 - 50) = 26$
2. Accumulated GDD in 7 days is $[1150 + (26)(7)] = 1332$

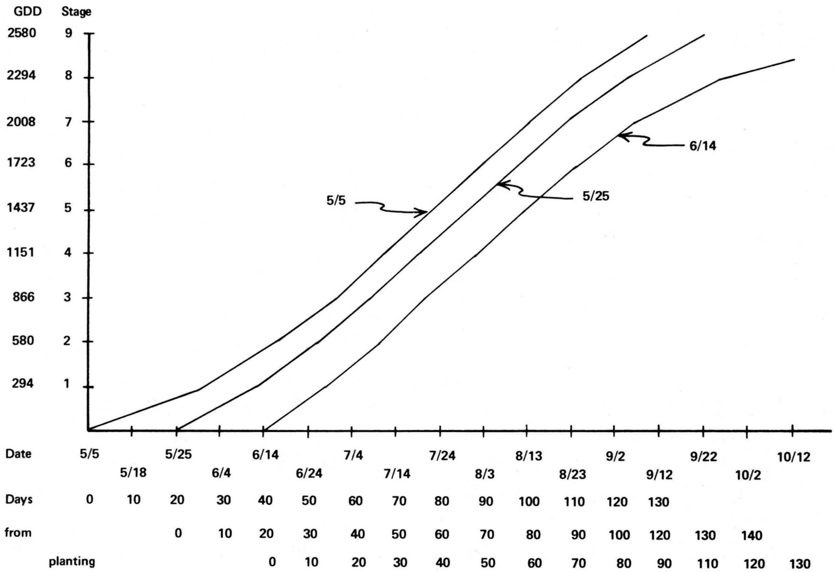

Figure 5. Grain sorghum hybrid RS 671 planted at Gothenburg May 5, May 25 and June 14.

3. [(.0038)(1132) − .31] = 4.75

If the temperature is 10°F above normal, or 86°F, the hybrid would be at stage 5.02 or tasseling in one week. If it is 10°F below normal, the hybrid would be expected to be at stage 4.49, half-way between "16 leaf" and tasseling, in one week.

Estimating number of days to a future stage of development is a similar possible prediction. For example, there are 1400—1150, or 250 GDD, between stage 4 and stage 5. Assume that Neb 611 is at stage 4 (accumulated 1150 GDD) on 7/14. If normal temperatures prevail, it will require 250 ÷ 26 = 9.6 days before tasseling. Only 7 days would be required if future temperature is 10° above normal (86°F). Fifteen days would be required if the temperature is 10° below normal (66°F).

5. Estimating the number of days that a growing season is ahead or behind normal. Data from the 1972 growing season at Lincoln, Nebraska, Table 3, are used to illustrate this procedure. In the table are the normal accumulated GDD, 1972 accumulated GDD, the differences between normal and 1972 GDD, the normal GDD per day, and the difference in days that the 1972 season is ahead (+) or behind (−) normal for different dates. The days ahead or behind are determined by dividing the difference in accumulated GDD by the daily normal GDD. For example, the 1972 season was 156 GDD or 156 ÷ 28 = 5.6 days behind normal on 7/15. It was 7.3 days behind on 7/30, 11.7 on 8/15, 2 weeks behind on 8/30, 3 weeks behind on 9/15 when corn

Table 3. Progress of 1972 growing season at Lincoln compared with normal.

Date	Accumulated GDD Normal	Accumulated GDD 1972	GDD difference	Normal GDD per day	Days difference
6/15	762	708	−54	23	−2.3
6/30	1130	979	−151	26	−5.8
7/15	1534	1378	−156	28	−5.6
7/30	1954	1751	−203	28	−7.3
8/15	2395	2078	−317	27	−11.7
8/30	2774	2448	−326	23	−14.2
9/15	3112	2711	−401	19	−21.1
9/30	3332	2907	−425	13	−32.7

harvest usually first begins, and a month behind on 9/30 when corn harvesting activity usually is at a peak in eastern Nebraska.

The following statements from the Weekly Weather and Crop Report (1972) for Nebraska show the sequence of developments that season.

July 31 – "Weather favorable for row crops. Crop maturity advancing rapidly with 70% of corn silking, 35% of sorghum heading and 32% of soybeans podding."

September 4 – "Both irrigated and non-irrigated corn, good to excellent."

September 25 – "Corn development slow, with 52% mature, compared with 63% normal."

October 16 – "Grain dried slowly. Grain sorghum 25% harvested, last year 72%, normal 32%. Moisture content averages 20%, 15% a year ago.

October 30 – "Harvest progress slower than normal and far behind last year's early harvest."

November 6 – "Rain and snow across state stopped all harvesting first part of week. Grain that was dry last week now too wet for safe storage."

November 20 – "Paramount weather was severe. Losses in section of east and south. Crop losses vary between areas. Generally sorghum damaged about twice as much as corn."

November 27 – "Harvest of corn and sorghum resumed last week but progress very slow. Drying equipment critical factor in some areas."

Data in Table 3 are an example of the use of GDD to provide an early quantitative measure of a developing adverse crop-weather situation.

6. *Use of crop observations to improve growing degree day predictions.* The crop itself is the ultimate integrator of all its environmental variables. Growing degree days measure only temperature effects. Observations from a "standard planting" of a hybrid representative of the

crop acreage in a given area may therefore be used to improve GDD predictions. For example:

Data in Table 1 showing GDD requirements for different stages and hybrids shows Neb 611 should be at stage 0.5 (2 leaves), when 213 GDD have accumulated. Dry soil may delay germination even though temperature conditions are favorable. More than 213 GDD, assume 290 GDD, may accumulate between planting and the "2 leaf stage" in such instances. Stage 1 (four leaves), is predicted at 350 − 213 = 137 GDD from stage 0.5, so would be expected to occur when 290 + 137 = 427 GDD have accumulated this season instead of 350. A crop on a warm site (sandy soil and south facing slope) may reach stage 0.5 with fewer than 213, assume 170 GDD accumulated. In this instance, stage 1 would be expected when 170 plus 137 or 307 GDD have accumulated.

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