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Improved Crop Coefficients for Irrigation Scheduling

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IRRIGATION SCHEDULING

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Steven Hinkle	1980, 1981	Rogers Farm	Corn
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INTRODUCTION

The use of water for irrigation is receiving more scrutiny as supplies are reduced, competing demands emerge, and application costs increase. Improved water management in irrigation requires an accurate scheduling of irrigations. In areas experiencing limited water supplies, this may involve scheduling irrigations to obtain maximum return per unit of water applied. Other areas may require scheduling to limit deep percolation of water and other valuable nutrients.

The adoption of irrigation scheduling programs such as those described by Kincaid and Heermann (1974) has resulted in reduced application of water. These programs provide estimates of when and how much to irrigate by using daily weather data and other data related to the specific crop and soil situation under consideration. With irrigation scheduling, excessive irrigation can be reduced, considerable energy can be saved, and nutrients can be put to more efficient use.

A necessary requirement within the irrigation scheduling program is the accurate calculation of daily crop evapotranspiration (ET). The current methodology of estimating crop ET is the use of a potential or reference ET and a crop coefficient. The crop coefficient is an empirical ratio of crop ET to some reference ET, and is generally derived from experimental data. The crop coefficients currently being used are generally presented as a function of time, usually as a percentage of elapsed time from planting to full cover for the first part of the growing season, and days after full cover for the last part of the growing season.

To provide a basis for directly relating the crop coefficient to crop development and to account for changes from normal weather conditions, field experiments to develop improved crop coefficients were conducted at two sites in Nebraska. The independent variables used to describe the crop coefficient were cumulative growing degree days and stage of growth. The crop coefficients presented in this report are daily basal values, representing conditions when soil evaporation is minimal, but the availability of soil water within the root zone does not limit plant growth or transpiration.

METHODS AND MATERIALS

LOCATION, CLIMATE AND SOILS

The field experiments conducted to develop improved crop coefficients were performed at two different experimental sites. Site one was at the Sandhills Agricultural Laboratory (41°37' N latitude; 100°50' W longitude; 975 m above sea level) in McPherson Co. near Tyron, Nebraska. Site two was at the Rogers Memorial Farm in Lancaster Co. near Lincoln, Nebraska (40°49' N latitude; 96°42' W longitude, 350 m above sea level). Both sites are research facilities of the University of Nebraska. Lysimetric measurements of crop evaotranspiration (ET) were made at the Sandhills Agricultural Laboratory during 1978, 1980 and 1981, and at the Rogers Memorial Farm during 1980, 1981 and 1982.

The Sandhills Ag. Lab. (SAL) site has a semiarid climate with an average annual rainfall of 53.6 cm (21.1 in). It is situated in the native grass covered rolling sandhills of west central Nebraska. Hot dry southerly winds, warm days, and cool nights are characteristic of its summer weather. Soils at the Sandhills Ag Lab are a coarse textured Valentine very fine sand to a loamy fine sand (Typic Ustipsament).

The Rogers Farm site has a subhumid climate with an average annual rainfall of 74.2 cm (29.2 in). It is situated in the rolling hills of southeastern Nebraska that developed from erosion of loess deposited plains. Occasional dry southerly winds, hot and humid days, and warm nights characterize the growing season. Soils at the Rogers Farm are a fine textured Sharpsburg silty clay loam (Typic Argiudolls).

LYSIMETERS

Hydraulic lysimeters similar to a design by Hanks and Shawcroft (1965) were used for ET measurement at both locations. Modifications to the basic design were made to further minimize temperature and atmospheric pressure effects by using a "dummy" lysimeter and mercury for a portion of the standpipe fluid (Duke, 1980). In theory, the lysimeters have an approximate precision of ± 0.1 mm of measured ET, which is acceptable for measuring evapotranspiration on a daily basis. A side and end view of the lysimeter are shown in Figure 1.

The lysimeters had inside dimensions of 76.2 cm by 152.4 cm by 111.8 cm depth (30 in by 60 in by 44 in depth). They were constructed of 1.90 cm (0.75 in) pressure treated plywood and reinforced with 5.08 cm (2 in) angle iron at all the edges. Three rectangular frames of angle iron were placed on the inside walls of the inner box to minimize wall deflection due to lateral soil pressure. In addition, three angle iron frames were placed around the outside of the outer box to serve the same function. A flexible rubber backed canvas covered the space between the inner and outer boxes of the lysimeter.

The inner box of the lysimeter rested on bags or "pillows" consisting of "lay-flat" rubber irrigation hose made from nylon reinforced butyl rubber. The ends were folded over and vulcanized, and a rubber valve stem boot was vulcanized near one end. The pillows were filled with a 50 percent solution of automotive antifreeze (ethylene glycol) and water. A combination of copper and polyethylene tubing was used to transmit the hydraulic pressure to a central readout box which contained the manometer and standpipe setup for each lysimeter.

The manometer system used two different liquids to counter balance the lysimeter hydraulic pressure. A 50 percent solution of ethylene glycol and water was used throughout most of the manometer system. However, a section of mercury was used to lower the standpipe liquid level to within the dimensions

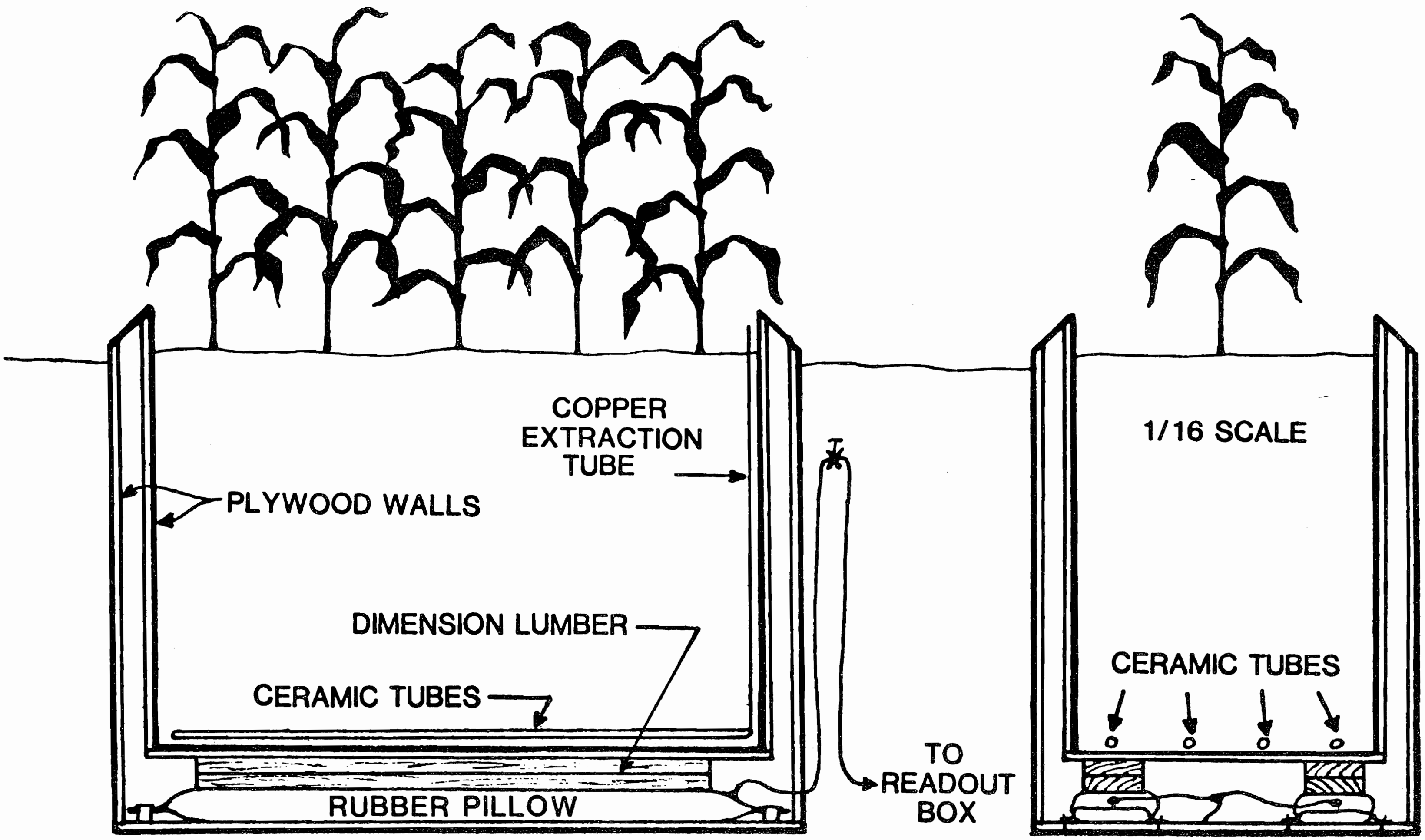

Figure 1. Side and end cross sectional views of the hydraulic lysimeters used in these experiments.

of the readout box that contained the manometer and standpipe setup for each lysimeter (Figure 2). Evapotranspiration of the crop in each lysimeter was determined by reading the liquid level in the standpipe of each lysimeter.

A temperature and atmospheric pressure compensating device was used in the ET determination (Figure 2). This consisted of a piece of plastic pipe closed on one end, covered with a rubber membrane on the other end and a lead weight placed on the rubber membrane. This device, referred to as a "dummy" lysimeter, was filled with the antifreeze-water solution and connected to its own manometer and standpipe setup. Changes in the standpipe level of the "dummy" lysimeter were assumed to be due to changes in temperature and/or atmospheric pressure and were subtracted from the standpipe level change of all the lysimeters.

The lysimeters contained a vacuum drainage system to remove any gravitational water resulting from a large rainfall. This system consisted of 1.27 cm (1/2 in) outside diameter, one bar ceramic tubes connected to a copper manifold and extended to the top of the lysimeter (Figure 1). These tubes were then connected with vinyl tubing to a 18.9 liter (5 gal) glass collection container which was supplied with vacuum from a central vacuum system.

Utilizing the temperature and atmospheric pressure compensating device, the equation for ET calculation was:

$$ET = c_i\,(\Delta \text{ standpipe level} - \Delta \text{ dummy standpipe level}) + \text{Rain} + \text{Irrigation} - \text{Drainage} \quad (1)$$

The calibration coefficient, c_i was unique for each lysimeter and was determined empirically, by loading the lysimeter with weights and observing the standpipe level change. A linear regression was then used to obtain the calibration coefficient.

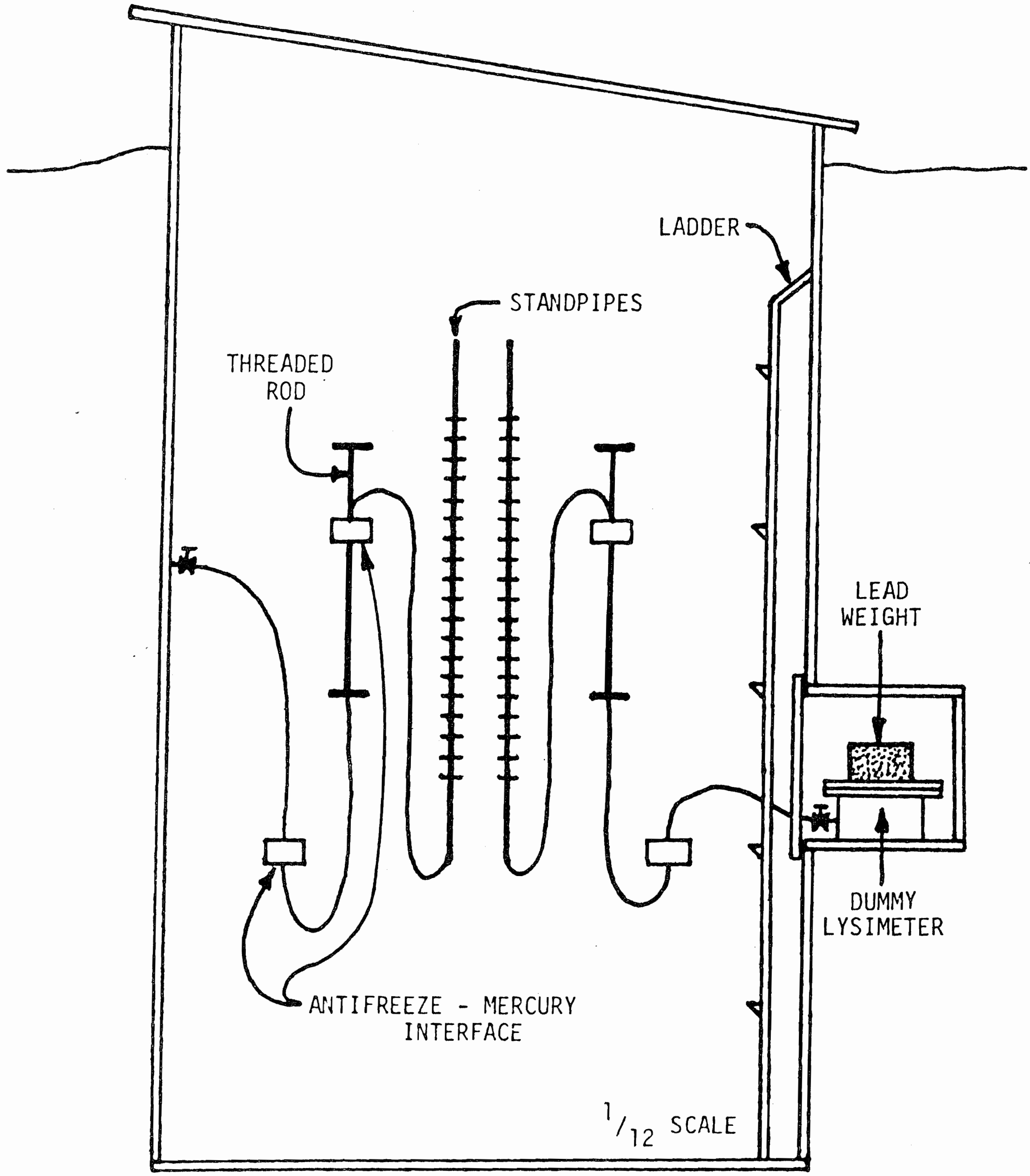

Figure 2. Cross sectional view of the lysimeter readout box showing the manometers and standpipes.

Rainfall was measured at a central weather station located near the lysimeters. Irrigation was measured by using four raingauges at each lysimeter, one placed near each corner. Rainfall and drainage amounts were measured at the same time that the lysimeter were read.

Each lysimeter had two 5.08 cm (2 in) aluminum access tubes installed within the lysimeter. Two additional tubes were also placed within the cropped area just outside each lysimeter. These tubes were used for measuring soil moisture with a neutron scatter device. The soil moisture measurements were used to schedule irrigations and to determine evapotranspiration by a separate water balance approach. Measurements were made on a weekly basis so that weekly and seasonal ET amounts could be calculated and compared to results obtained from the lysimeters.

Special care was taken to maintain the soil and microclimate environments in and around the lysimeters. The soil used inside each lysimeter was the soil that was excavated at the site of each lysimeter. In addition, the soil was removed in 30 cm (12 in) layers and backfilled in the same order as removal. The soil was not pulverized or conditioned in any way before being backfilled. The soil area around the lysimeters was landscaped so that the elevation of the soil surface outside and inside the lysimeters was approximately the same. Plants around the lysimeters were thinned to the correct population and proper spacing to help maintain the microclimate throughout the lysimeter region.

IRRIGATION SYSTEM

Irrigation to the lysimeters at both locations was provided by a underground solid set sprinkler system. Design and layout of the system was similar at both locations. The typical layout of the system and the location of the lysimeters with respect to the system are shown in Figure 3.

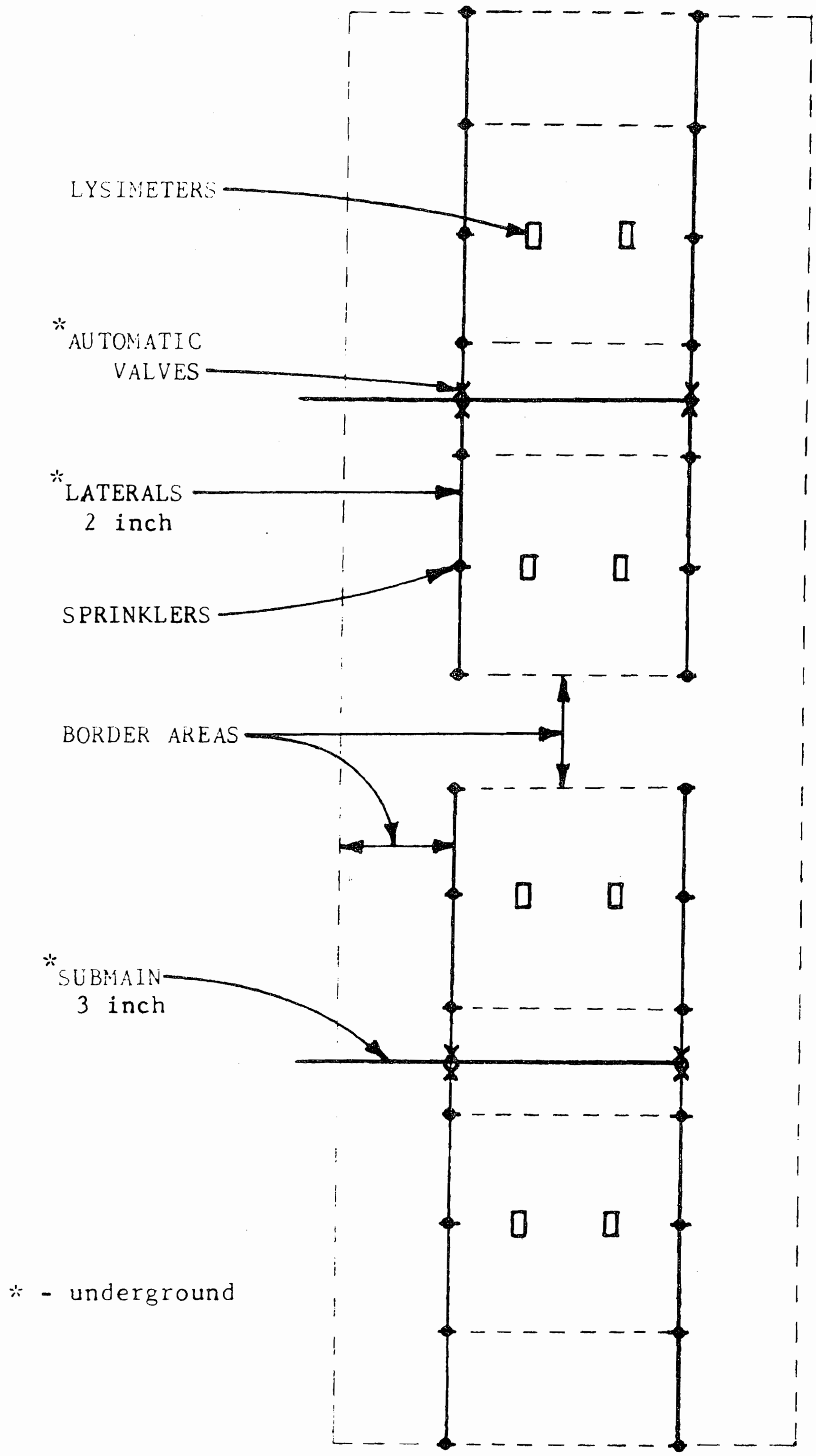

Figure 3. Typical layout of the lysimeters and the irrigation design used in these experiments.

The location of the lysimeters with respect to the irrigation system was the same at both sites. The lysimeters were situated with their longest dimension parallel to the underground pipeline lateral so the 0.76 m (2.5 ft) corn rows were planted parallel to the lateral. The lysimeters were located 6.1 m (20 ft) from a lateral and directly adjacent to a riser on the lateral.

The sprinklers and the riser design were also similar at both locations. Sprinklers at SAL were Rainbird model 30E with 3/16" x 3/32" nozzles, which had a radius of throw of approximately 16.8 m (55 ft) and an application rate of approximately 11.4 mm/hr (0.45 in/hr). Sprinklers at the Rogers Farm were Rainbird model 30EH with straightening vanes and 13/64" nozzles, which had a radius of throw of approximately 16.8 m (55 ft) and an application rate of approximately 10.7 mm/hr (0.42 in/hr). Risers were built from polyethylene tubing, steel posts, and steel and plastic pipe fittings and were between 2.1 and 2.4 m (7 to 8 ft) tall.

The sprinkler and lysimeter layout provided good water application uniformity. Foremost, the layout was bilaterally symmetrical about a line directly between the laterals. Secondly, the location of the lysimeters enabled them to be irrigated by six different sprinklers. Finally, the irrigation system generally had less than six sprinklers per lateral so that friction losses along the lateral were small.

The irrigation systems were controlled by automatic controllers which helped provide the most optimum system operation. The controller could be programmed to begin during the late evening or early morning when winds were normally calm and the irrigation uniformity during these times was quite high.

BASAL CROP COEFFICIENTS

The crop coefficients (Kco) that are presented in this report are defined as the crop evapotranspiration (ET) divided by a potential ET of some reference crop, and are all basal equations, i.e., they predict the crop coefficient for normal, dry surface conditions. Two methods were used to determine the basal Kco equations. Method one simply deleted the ET data taken on the few days following a rain or an irrigation event. Method two involved correcting the measured ET values taken after a rain or irrigation to basal values.

Evapotranspiration values for the two to three days after a rain or irrigation at SAL during 1978 and 1980 were deleted from the data sets before the crop coefficient equations were calculated. Infrequent rainfall events and the coarse textured soils allowed the use of this method at SAL during the years of 1978 and 1980.

The second method was used on the 1981 ET data from SAL and all the data from the Rogers Farm because of more frequent rainfall events. The ET values from these data sets were changed to basal values by using an ET model and a soil drying equation to estimate the additional soil evaporation taking place following a rain or irrigation and subtracting the result from the measured ET values. The ET model was developed by Ritche (1972) and utilizes the leaf-area index and weather data to estimate soil and plant evporation. In this study, only the portion that calculated potential soil evaporation (Ep) below the crop canopy was used.

The potential soil evaporation values below the crop canopy were used together with a soil drying equation by Hanks (1974) to determine dry soil surface evaporation rates:

$$E = Ep \quad , \text{ stage I drying} \qquad (2)$$

$$= Ep\,(tp/t)^{1/2} \quad , \text{ stage II drying, } t > tp$$

E = soil evaporation rate, mm/day

Ep = potential soil evaporation rate, mm/day

tp = time of stage I drying, days

t = time since a rain or irrigation, days

Hanks used a value of one day for the time of stage I drying and Ritchie used a maximum cumulative stage I evaporation value to determine the end of stage I drying. These values were found from drying experiments using lysimeters on a variety of different soils. However, the duration of stage I was generally between 1.0 and 1.5 days for the different soils. Therefore, one day was assumed for the stage I drying time in these experiments.

The evaporation rate after six days in equation 2 was used as the basal, dry surface evaporation rate. Six days was judged as sufficient time for the soil surface to dry with or without a crop canopy for the silty clay loam soils at the Rogers Farm and more than sufficient time for the sandy soils at SAL. Integration of equation 2 for stage II drying and subtracting the basal evaporation rate gives an equation for the additional evaporation after a rain or irrigation:

$$Eadd = 0.59\ Ep\ ; \quad \text{stage I, first day after a rain or irrigation} \qquad (3)$$

$$= (\ 2\ (t^{1/2} - (t - 1)^{1/2}) - 0.41\ )\ Ep, \quad \text{stage II for t of 2-6 days after a rain or irrigation}$$

Eadd = additional daily evaporation after a rain or irrigation, mm/day

Ep = potential soil evaporation below the crop canopy calculated using the technique from Ritchie (1972), mm/day

t = days after a rain or irrigation.

These equations were used to predict the additional evaporation after a rain or irrigation and thus the basal ET values at the Rogers Farm and at SAL during 1981.

Both linear and polynomial equations were used to describe the crop coefficients obtained from these experiments. The following equations are used throughout the report to describe the results:

<u>Linear model</u>

initial horizontal portion

$$Kco = e; \quad o \leq x \leq c \tag{4}$$

increasing portion

$$Kco = a + bx; \quad c < x < d \tag{5}$$

peak horizontal portion

$$Kco = f; \quad d \leq x \leq p \tag{6}$$

decreasing portion

$$Kco = g + hx; \quad p < x \leq q \tag{7}$$

where x is the independent variable.

<u>Polynomial model</u>

initial horizontal portion

$$Kco = F; \quad o \leq x \leq r \tag{8}$$

remaining portion

$$Kco = A + Bx + Cx^2 + Dx^3 + Ex^4; \quad r < x \leq s \tag{9}$$

where x is the independent variable.

A number of independent variables were used to describe the crop coefficients. These included time, cumulative growing degree days from emergence (GDD), fraction of GDD from planting to maturity, and stage of growth.

RESULTS AND DISCUSSION

CORN EXPERIMENTS

The corn varieties selected for these experiments exhibited a wide range of maturity. The specific varieties, their approximate maturity lengths for this region, the approximate average number of leaves developed by each variety, and the variety designation as used in this report are given in Table 1.

Planting and emergence dates were unique for a particular location and year, and are summarized in Table 2. Plant populations used in the lysimeters varied between varieties, years and locations and are summarized in Table 3.

Growth Parameters

Leaf area and stage of growth were generally measured one or two times per week. Leaf area was measured with a Licor model LI-3000 portable leaf area meter and the leaf area was divided by the land area to obtain the leaf area index (LAI). Stage of growth was characterized by using the scale developed by Hanway (1971) which is summarized in Table 4.

The scale developed by Hanway (1971) implies the development of four fully emerged leaves per stage or twenty total leaves during the vegetative period. If a particular variety did not develop twenty total leaves, the following modification was made:

$$Stage_i = \frac{\text{No. of current fully emerged leaves}}{\text{Total no. of fully emerged leaves}} \times 5 \qquad (10)$$

where i is the stage number, 1 through 5.

This modification was needed because the range of total fully emerged leaves for the varieties involved in this experiment was between 15 and 22 leaves. The approximate number of leaves that each variety developed is given in Table 1.

Table 1. Corn varieties grown at the Rogers Memorial Farm and the Sandhills Ag Lab during the study period.

Variety	Approximate Maturity Length days	Average No. of Total Leaves	Variety Designation
Dekalb DK24	80	15.4	VAR80
Dekalb XL6	85	16.7	VAR85
Pioneer 3901	100	18.5	VAR100
Pioneer 3780	101	19.0	VAR101
A619 x A632	105	19.4	VAR105
M017 x A634	110	20.0	VAR110
M017 x B73	120	20.4	VAR120
Dekalb XL395	140	22.0	VAR140

Table 2. Planting dates and emergence dates for each location and year for the corn experiments.

Location-Year	Planting Date	Emergence Date
SAL78	May 19, 1978	May 27, 1978
SAL80	May 7, 1980	May 20, 1980
SAL81	May 22, 1981	May 31, 1981
ROG80	May 7, 1980	May 20, 1980
ROG81	May 7, 1981	May 22, 1981

Table 3. Plant populations for the corn lysimeter experiments.

		Corn Variety [a]							
Year	Location	VAR80	VAR85	VAR100	VAR101	VAR105	VAR110	VAR120	VAR140
1978	SAL			1,2,3,4	1,2,3,4,				
1980	SAL							2,3,4	
	Rogers Farm							2,3,4,	
1981	SAL	4	4	4	4		4	4	4
	Rogers Farm	4	4	4		4		4	4

1 - 34444 pl/ha (13939 pl/ac)
2 - 43056 pl/ha (17424 pl/ac)
3 - 60279 pl/ha (24394 pl/ac)
4 - 77500 pl/ha (31363 pl/ac)

[a] Variety description is given in Table 1.

Table 4. Hanways stages of corn growth. [1]

Stage	Identifying Characteristics
0	Plant emergence.
1	Collar of 4th leaf visible.
2	Collar of 8th leaf visible.
3	Collar of 12th leaf visible.
4	Collar of 16th leaf visible. Tip of tassle may be visible.
5	75 percent of silks visible. Pollen shedding.
6	Kernels in blister stage.
7	Kernels at dough stage. (very late roasting ear)
8	Kernels beginning to dent.
9	Kernels fully dented.
10	Physiological maturity. Black layer formed. Grain fill complete.

[1] From Hanway (1971).

An evaluation was made to determine a temperature or solar radiation factor or some combination of both that best predicted corn development as indicated by stage of growth. Stage of growth data for the Rogers Farm and for the Sandhills Ag. Lab. were available for up to five different years and up to seven different corn varieties (Table 5).

The different factors for predicting stage of growth that were evaluated in this study were: time, cumulative Jensen-Haise ETp, and cumulative growing degree days (GDD) with different temperature limits. The different GDD methods (all using °F) included 50-86, 50-90, 50-95, 50-no upper limit, no lower or upper limit, and a 50-90 heat stress method. The last method is called a stress method because the upper limit is not just a limit for the maximum value of temperature, but actually further reduces it by the amount that measured maximum temperature exceeds the upper limit. The 50-90 stress method alters maximum temperature as follows:

$$T_{max} = T_{max} \; ; \quad \text{if } T_{max} \text{ is} \leq 90° \text{ F.} \qquad (11)$$

$$T_{max} = 90 - (T_{max} - 90) \; ; \quad \text{if } T_{max} \text{ is} > 90° \text{ F.} \qquad (12)$$

Linear regressions of stage of growth versus the cumulative growth factors were made and compared. The comparisons included standard errors of estimate and correlation coefficients for individual situations and the similarity of the regression coefficients and intercepts among the different years and locations.

The selection of the different temperature and solar radiation combinations was a result of a literature review of the factors that influence corn growth (Mederski, et al., 1973; Cross and Zuber, 1972; and Gilmore and Rogers, 1958). These authors compared variations of GDD with different upper limits and with a 10°C (50°F) base temperature. Lahenbauer (1914) and Coelho and Dale (1980) found that corn grew very little or not at all below 10°C (50°F) and that the

Table 5. Stage of growth data used in the stage of growth analysis.

	Variety						
Location Year	PIONEER 3901	MO17 x B73	A619 x A632	ACCO U322	DEKALB DK24	DEKALB XL6	MO17 x A634
SAL							
1977	X	X	X				
1978	X						
1979	X						
1980	X						
1981	X	X	X	X	X	X	X
Rogers Farm							
1980	X	X		X			
1981	X	X	X		X	X	X

rate of growth increased almost linearly with increased temperature up to approximately 30 to 32°C (86 to 90°F). Above 32°C, the rate of growth decreased with increasing temperature. Cumulative Jensen-Haise ETp and GDD with no limits and a 10°C (50°F) base were selected because of their use by some agricultural and government groups.

Partial results for one corn variety, Pioneer 3901, for two years at both locations are summarized in Figures 4 through 9. Correlation coefficients and standard errors of estimate for the different GDD methods are given in Tables 6 and 7, respectively.

Although the use of time as the independent variable appears to be as good a predictor of growth stage as the GDD methods, it is not a good basis for predicting growth. While time has a lower standard error of estimate than two of the GDD methods (Table 7), it has more variation earlier in the season than the GDD methods (Figures 4-9), and there is also more variation in the standard error of estimate among the particular years and locations. Mederski, et al. (1973) found all GDD methods to be superior to time as a predictor of corn growth. They, along with Coelho and Dale (1980) and Gilmore and Rogers (1958), all felt that temperature is the most important factor affecting the rate of corn growth.

Cumulative Jensen-Haise ETp is a poor basis for predicting corn growth among different years and locations (Figure 5). While the standard errors of estimate for individual years and locations are as good as the GDD methods, the overall standard error of estimate is too large for cumulative Jensen-Haise ETp to be useful for predicting corn growth.

The results of stage of growth versus cumulative GDD calculated with no limits and with only a 50°F lower limit are shown in Figures 6 and 7, respectively. The two methods are clearly better than the Jensen-Haize method but

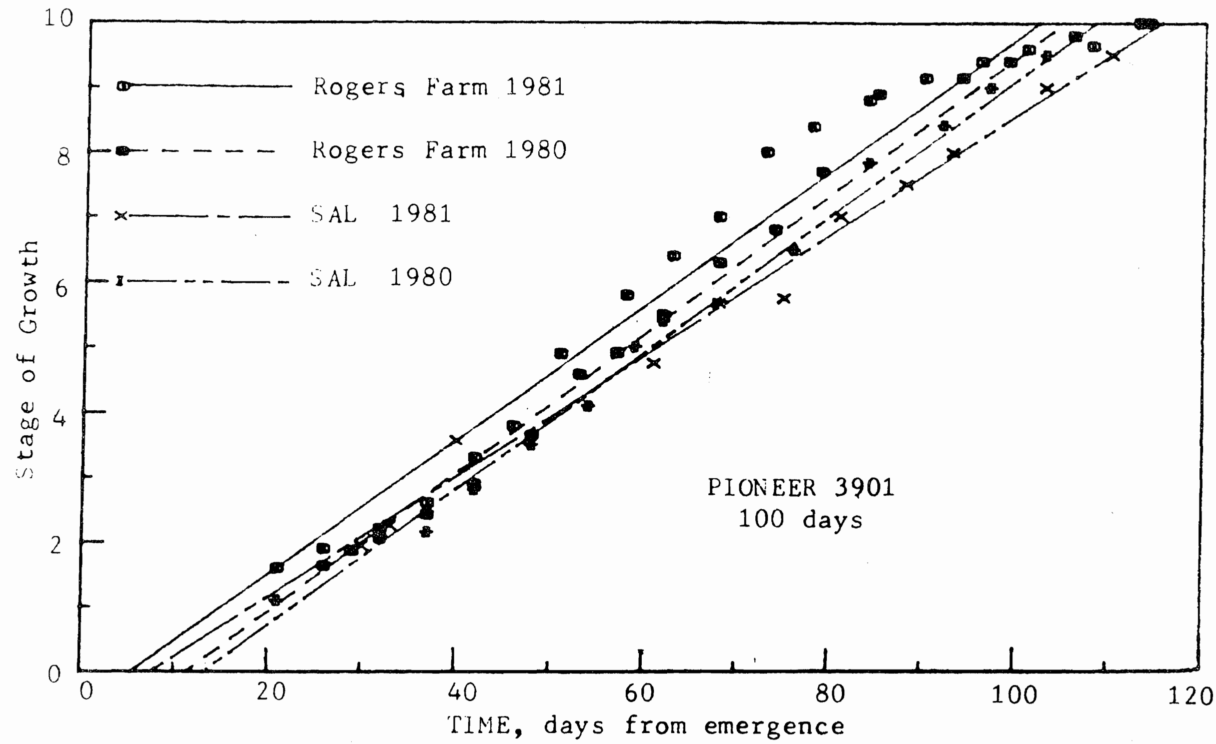

Figure 4. Stage of growth versus time for Pioneer 3901 for two years and two locations.

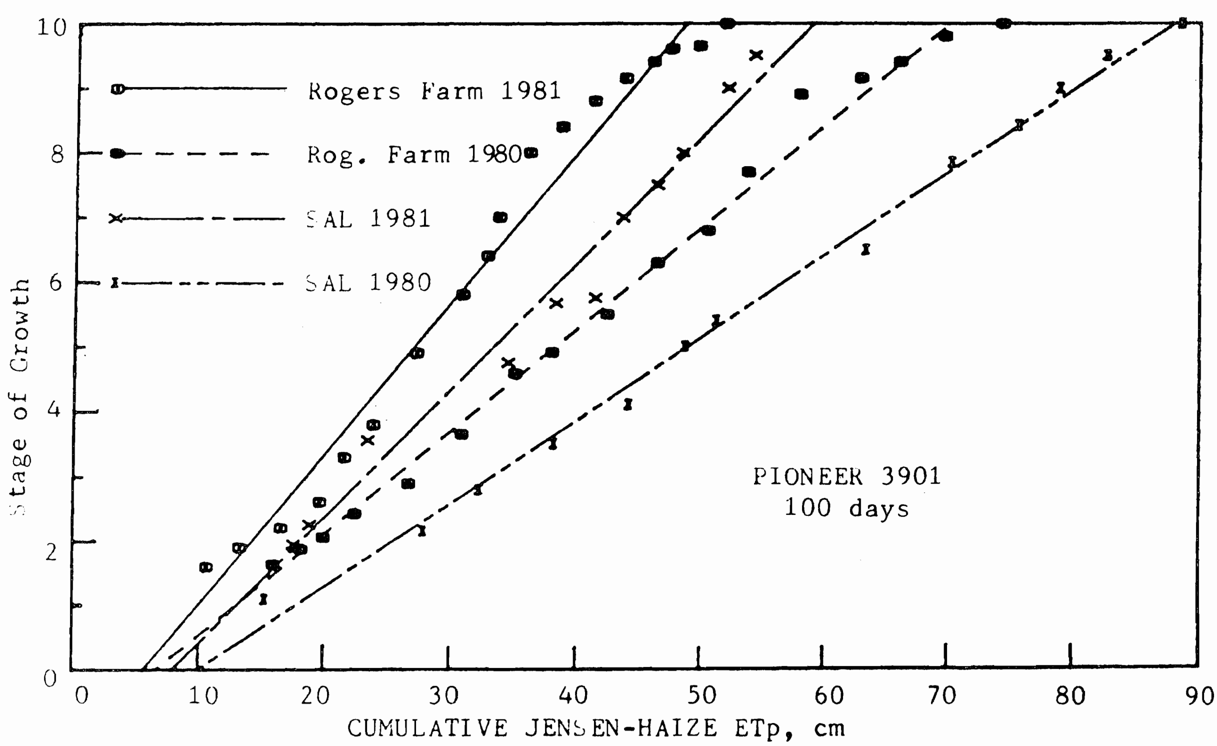

Figure 5. Stage of growth versus cumulative Jensen - Haise Etp for Pioneer 3901 for two years and two locations.

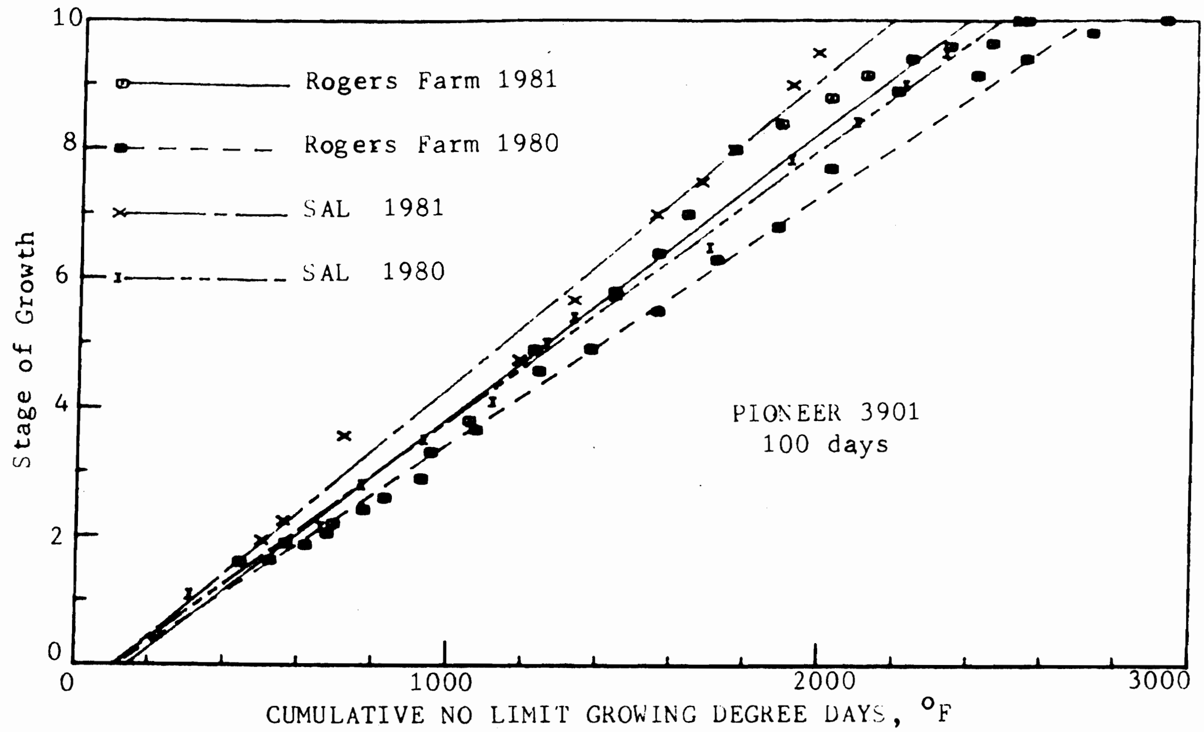

Figure 6. Stage of growth versus cumulative no limit growing degree days for Pioneer 3901 for two years and two locations.

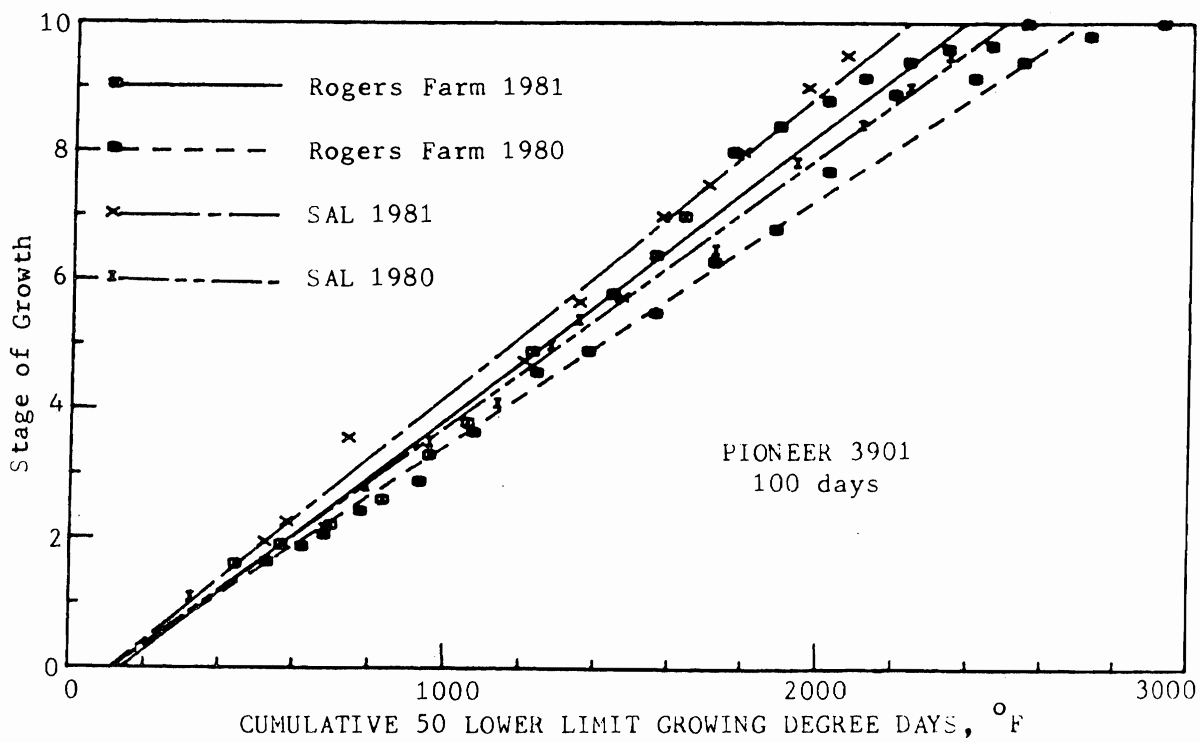

Figure 7. Stage of growth versus cumulative GDD with only a 50°F lower limit for Pioneer 3901 for two years and two locations.

Table 6. Linear regression correlation coefficients for stage of growth vs. different independent variables for PIONEER 3901. [1]

Independent Variable	Site Year				
	SAL 80	SAL 81	Rogers 80	Rogers 81	Overall
Time	0.996	0.995	0.990	0.979	0.981
Jensen-Haise ETp	0.998	0.988	0.995	0.987	0.841
No Limit GDD	0.998	0.989	0.993	0.991	0.978
50-* GDD[2]	0.998	0.991	0.993	0.990	0.980
50-86 GDD	0.998	0.992	0.992	0.989	0.986
50-90 Stress GDD	0.998	0.993	0.991	0.989	0.986

[1] Model, stage of growth = a + b(factor).

[2] No uppper temperature limit.

Table 7. Linear regression standard errors of estimate for stage of growth vs. different independent variables for PIONEER 3901. [1]

Independent Variable	Site Year				
	SAL 80	SAL 81	Rogers 80	Rogers 81	Overall
Time	0.284	0.279	0.437	0.639	0.569
Jensen-Haise ETp	0.217	0.420	0.310	0.494	1.570
No Limit GDD	0.174	0.397	0.357	0.424	0.609
50-* GDD[2]	0.178	0.356	0.357	0.432	0.574
50-86 GDD	0.200	0.336	0.390	0.466	0.490
50-90 Stress GDD	0.212	0.328	0.415	0.472	0.476

[1] Model, stage of growth = a + b(factor)

2 No upper temperature limit.

actually are not as good as the time method. However, the GDD methods show better uniformity early in the growing season.

The results from the 50-86 method and the 50-90 stress methods of calculating GDD are shown in Figures 8 and 9, respectively. The regression coefficients and the predicted values of stage of growth are more nearly alike than the previous two GDD methods. The overall standard errors of estimate are smaller than the two previous methods. Of the two methods, the 50-90 stress method has the lower standard error of estimate than the 50-86 method.

The 50-90 stress method achieved more uniformity among years and locations than the 50-86 method but did not further reduce total cumulative GDD in more than half of the years. As the upper temperature limit is reduced along with a constant 50°F lower limit, less total GDD are accumulated and the regression lines naturally move closer together (Figures 7 and 9). The 50-90 stress method has a lower overall standard error of estimate for predicting stage of growth than the 50-86 method for this variety (Table 7). The same conclusions were also true for most of the other varieties evaluated. Other researchers also concluded that the 50-90 stress method of predicting corn growth was best (Cross and Zuber, 1972; Gilmore and Rogers, 1958).

Population Effects on Crop ET

An important factor relating population effects to crop evapotranspiration is the leaf area of the crop. Because crop transpiration is the major component of crop ET for most of the season (Ritchie and Burnett, 1971; and Hanks, 1974) and since transpiration is conducted almost entirely by the leaves, there should be strong relationship between leaf area and the crop ET.

Ritchie and Burnett (1971) developed a relationship between potential plant transpiration (Tp) and total potential soil and plant evaporation (Eo) as a function of LAI for grain sorghum and cotton. They explained that Tp becomes approximately equal to Eo only after the plant canopy has reached some "threshold" characteristic and only if the soil water supply is adequate. They obtained Tp/Eo ratio values of more than 0.9 when LAI values reached approximately 2.7. They further explained that once the threshold LAI value is reached, Tp plus soil evaporation was approximately equal to Eo but only if soil water was not limited.

Monteith, et al. (1965) reported that the crop resistance values for well watered barley were proportional to the inverse of the Tp/Eo values calculated by Ritchie and Burnett. Monteith, et al. (1965) further stated that the LAI did not greatly affect crop resistance after the LAI reached a value of approximately 3.0.

Measured amounts of ET, from emergence to maturity for three populations of VAR120 (MO17 x B73) at the Rogers Farm for 1980 are shown in Figure 10 and summarized in Table 8. There were two lysimeters of each population, however, one lysimeter containing the middle population became inoperative during the season. For the remaining five lysimeters, a one way analysis of variance indicated no statistical difference of ET from the different plant populations. The overall average seasonal ET was 69.1 cm (27.2 in) for the five lysimeters.

The LAI for the three populations of VAR120 (MO17 x B73) at the Rogers Farm during 1980 are shown in Figure 11. Comparing the LAI results in Figure 11 with the cumulative ET in Figure 10 shows that essentially all of the difference in ET among the three populations occurred during the initial growth period when the LAI was less than 2.7. On July 1, the ET difference between the high and low populations was 1.60 cm (0.63 in). On September 10, the ET difference

Table 8. Measured corn ET from emergence to maturity for three populations of VAR120 (MO17 x B73) at the Rogers Farm during 1980.

Julian Day	Population	Measured ET from Emergence, cm		Population Average ET, cm	Overall Average ET, cm
120	Emergence				
169	low	7.7	8.3	8.0	
	middle	8.6	--	8.6	
	high	8.4	9.3	8.8	8.4
199	low	26.0	29.4	27.7	
	middle	28.6	--	28.6	
	high	29.2	30.1	29.7	28.7
229	low	49.7	52.4	51.1	
	middle	51.9	--	52.0	
	high	53.0	53.6	53.3	52.1
259 maturity	low	67.1	70.0	68.4	
	middle	69.1	--	69.1	
	high	68.3	71.0	69.7	69.1

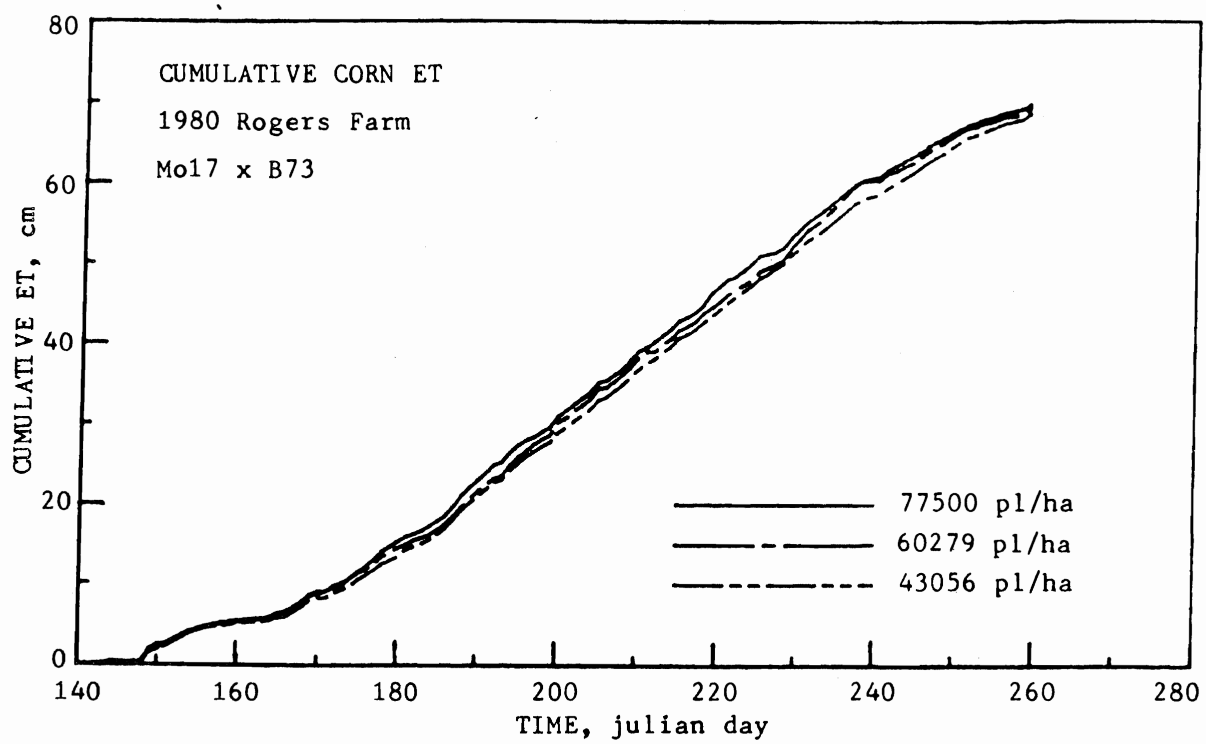

Figure 10. Cumulative corn ET for three populations of Mo17 x B73 at the Rogers Farm during 1980.

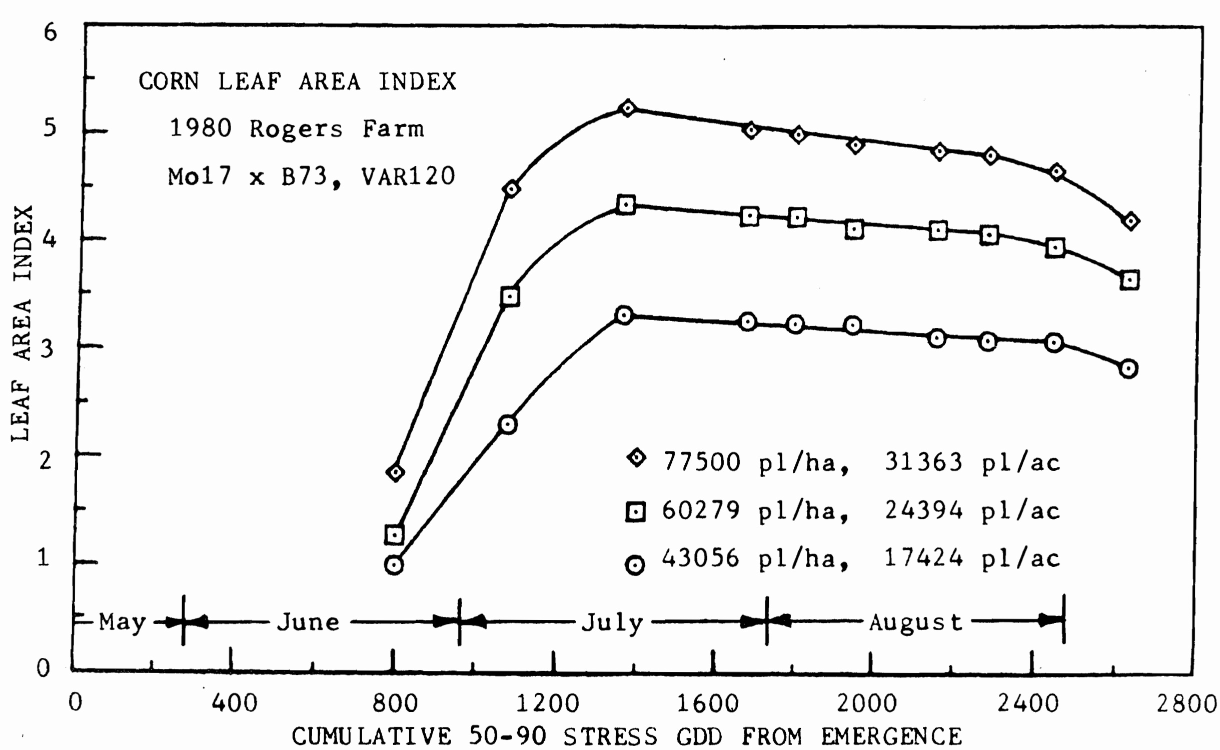

Figure 11. Corn leaf area index values for three populations of Mo17 x B73 at the Rogers Farm during 1980.

between the high and low populations was 1.57 cm (0.62 in). The ET difference between plant populations was essentially the same after all populations surpassed the threshold LAI of 2.7.

The LAI results shown in Figure 11 can also help to predict when the potential ET is reached, or when the crop coefficient equals one. The linear increasing Kco equation for the 1980 Rogers Farm for all populations (given later) predicts a Kco value of 1.0 at a fractional seasonal GDD of about 0.43 which is at 1190 cumulative GDD or about July 9th. This is when the lowest population surpassed the threshold 2.7 LAI (Figure 11).

In comparison, the same three populations of the MO17 x B73 corn variety grown at SAL during 1980 also showed no significant ET difference among plant populations (Figures 12 and 13). The corn at SAL was planted May 7th, the same day as this variety grown at the Rogers Farm. Average ET from stage 2 to stage 10 for all three populations at SAL was 62.5 cm (24.6 in) as compared to 59.7 cm (23.5 in) at the Rogers Farm. The crop at the Sandhills Ag. Lab. had a larger ET than that at the Rogers Farm within the same year primarily because of local weather differences. The time period from stage 2 to 10 was 78 days at SAL and 87 days at the Rogers Farm.

Lysimeter measured ET for the Pioneer 3901 variety (VAR100) at SAL during 1978 for four different populations (Figure 14) also showed no significant effect of plant population on ET (Kranz, 1981). The growth of tillers next to the main corn plants of the 43056 pl/ha population caused that population to accumulate more ET for the growing season (Figure 14). Because the leaves of the tillers matured later than the leaves of the main stem, transpiration was prolonged longer than normal and higher final ET levels were achieved. Cumulative lysimeter measured ET results for the Pioneer 3780 (VAR101) corn variety grown at SAL during 1978 (Figure 15) also showed no significant effect of plant population on seasonal ET (Kranz, 1981).

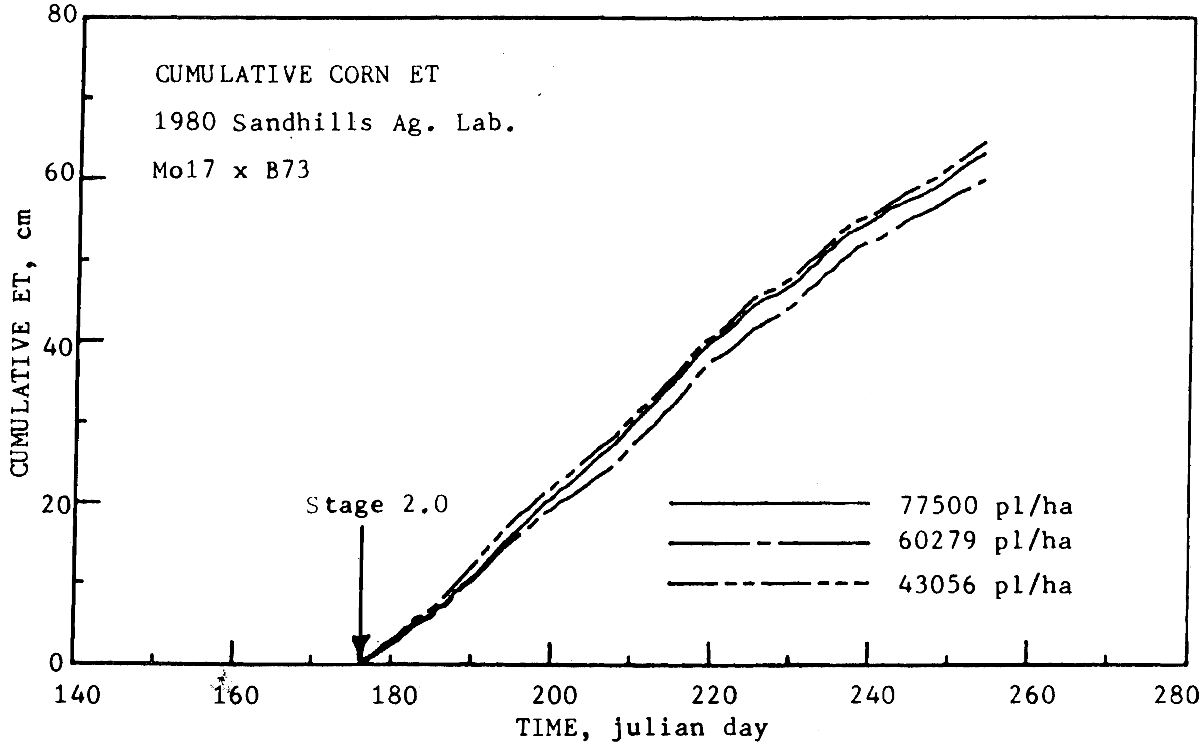

Figure 12. Cumulative corn ET for three populations of Mo17 x B73 at the Sandhills Ag. Lab. during 1980.

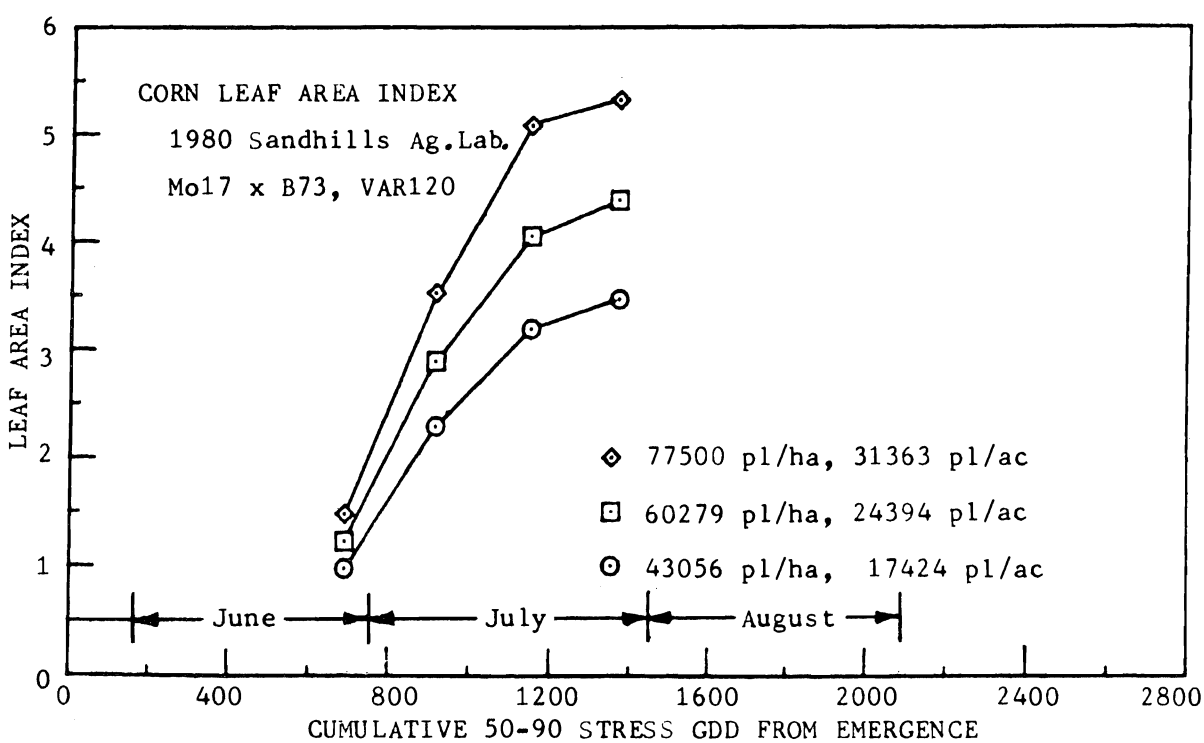

Figure 13. Corn leaf area index values for three populations of Mo17 x B73 at the Sandhills Ag. Lab. during 1980.

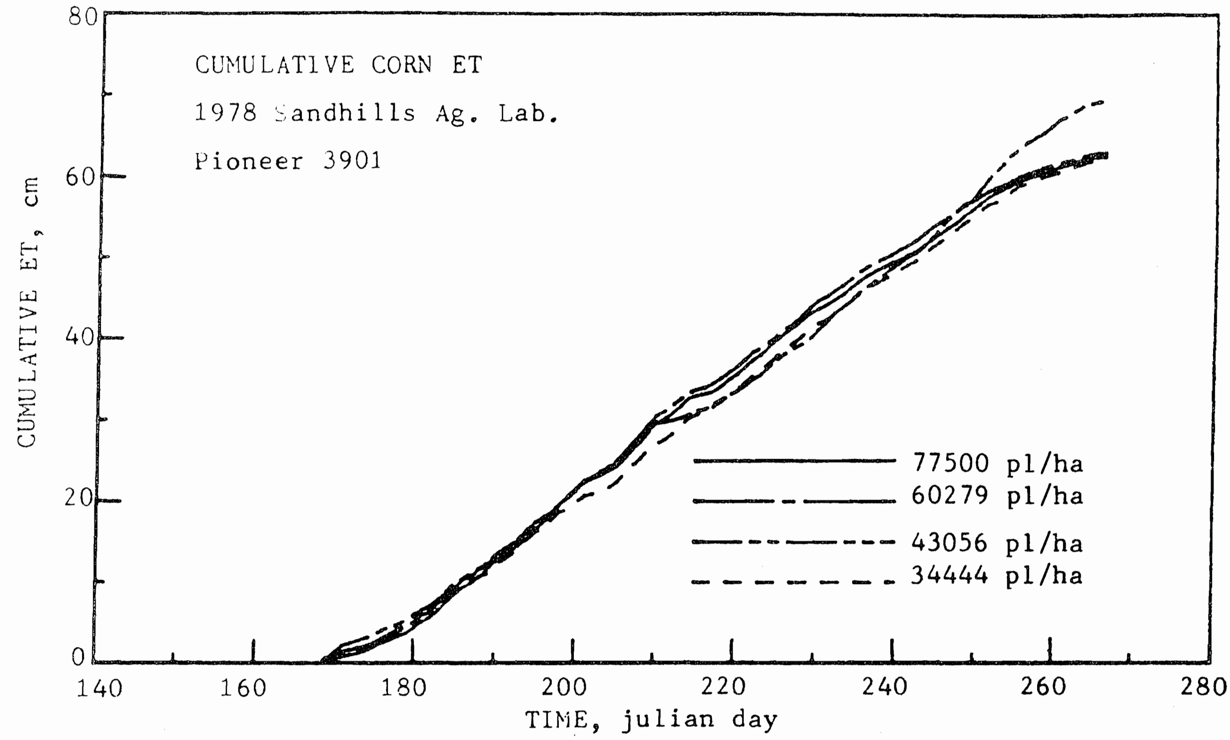

Figure 14. **Cumulative corn ET for four populations of Pioneer 3901 at the Sandhills Ag. Lab. during 1978.**

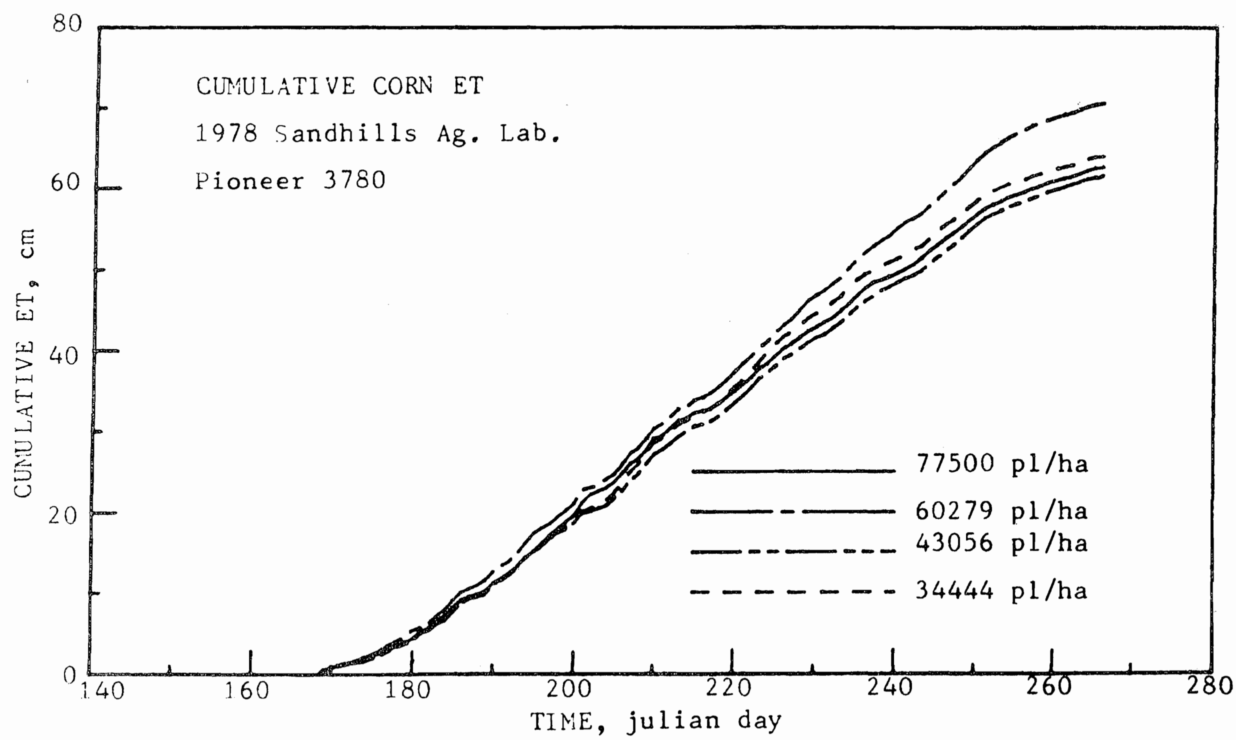

Figure 15. **Cumulative corn ET for four populations of Pioneer 3780 at the Sandhills Ag. Lab. during 1978.**

Comparing Pioneer varieties 3901 and 3780 (Figures 14 and 15) shows little difference in ET from stage 1.5 to 10. Both varieties were planted on May 19th and emerged on May 27th. Both varieties have essentially the same maturity length. However, the varieties differ in plant structure and leaf area development. All populations of the 3780 variety developed higher maximum leaf area than the same respective populations of the 3901 variety (Figures 16 and 17). This was because the 3780 variety has broader leaves and generally produced one more leaf than the 3901 variety. However, the LAI development early in the season was fairly similar.

The leaf area index results at SAL during 1978 also help confirm the relationship between LAI and ET (Figures 16 and 17). For the period of 800 to 1200 cumulative GDD or approximately July 10 to July 30, the most significant amounts of leaf area are accumulated and all populations surpass the 2.7 threshold LAI. At no time before effective full cover was there any significant difference in ET between the two varieties. Once LAI is greater than 2.7, or beyond effective full cover, crop ET is equal to potential ET and the level of LAI should have no effect on ET until senescence. Hence, for the rest of the season, no difference in ET should be expected if the varieties have the same maturity length.

For fully irrigated corn, plant population would appear to have little effect on the amount of total seasonal ET. Any reduction in transpiration due to lower plant populations was compensated with increased soil evaporation. However, if LAI is always below 2.7 (Ritchie and Burnett, 1971) which can occur at very low populations, then reduced seasonal ET levels could occur.

Crop Coefficients

Crop coefficient values for corn were determined from experiments conducted at the Rogers Farm during 1980 and 1981 and at the Sandhills Agricultural Laboratory during 1978, 1980 and 1981. Equations were developed to predict crop

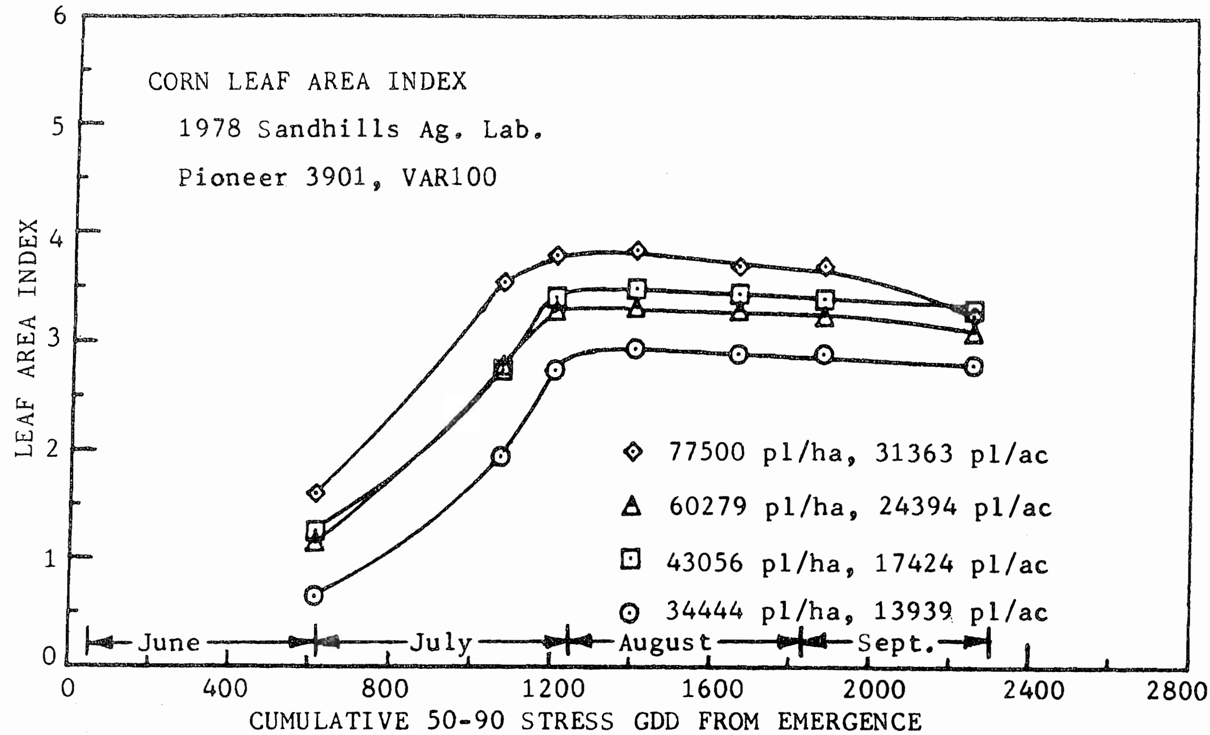

Figure 16. Corn leaf area index values for four populations of Pioneer 3901 at the Sandhills Ag. Lab. during 1978.

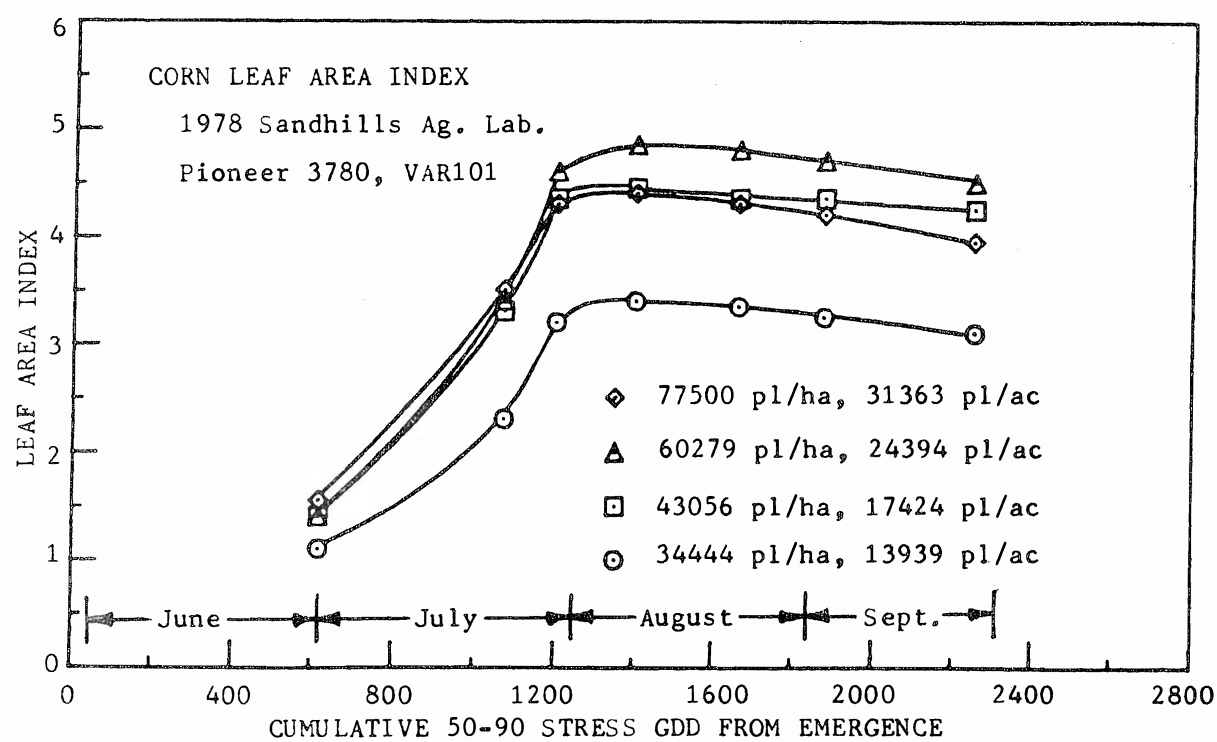

Figure 17. Corn leaf area index values for four populations of Pioneer 3780 at the Sandhills Ag. Lab. during 1978.

coefficient values as a function of different independent variables and for different segments of the growing season.

1980 Rogers Farm. Crop coefficient equations were first developed from the Rogers Farm lysimeter ET data using three populations of the VAR120 corn variety (Hinkle, 1981). The results of these experiments indicated there were no statistical differences in cumulative ET among the three populations. Therefore, the ET results from these populations were averaged and one daily value was obtained.

A number of equations were developed using the 1980 Rogers Farm ET values to determine which independent variables were the most practical for predicitng crop coefficients. The independent variables investigated included time, cumulative growing degree days (GDD) from emergence, fraction of GDD from emergence to maturity, and stage of growth. Single equations were defined across the entire season, and split season equations were defined before effective full cover and after effective full cover.

A number of conclusions were made from the analysis of the 1980 Rogers Farm data. Foremost, The 50-90 "heat stress" GDD method best predicted corn growth among varieties, years, and locations. Secondly, since Hanway's (1971) stage of growth scale defines stage zero as emergence, any independent variable should be expressed from emergence, and not from planting. Thirdly, any segmenting of the Kco equations should be done without splitting the season before and after some crop event so that the equations are more useful for crop modeling and for practical field use.

Attempting to split the season with two polynomials to try to obtain the best fit of equation(s) to the data points lead to numerous discontinuity problems. Straight line equations proved to be as effective or even better for defining the three periods (increasing, peak, decreasing) of the crop coefficient relationship. Expressing GDD as fraction of total GDD from emergence to maturity rather than total cumulative GDD from emergence enables the possibility of the equation to be universal for all varieties, irregardless of maturity length. This concept was then tested with subsequent experiments with different maturity length varieties.

As a result of the above conclusions, the 1980 Rogers Farm crop coefficient results were analyzed using fraction of total cumulative 50-90 stress GDD as the independent variable. An example of the relationships used to predict crop coefficients for the 1980 Rogers Farm data is shown in Figure 18. The fourth order polynomial equation is shown along with linear equations for the increasing and decreasing Kco periods, all as a function of fraction of total cumulative 50-90 stress GDD. Coefficients for the linear and polynomial models are given in Table 9.

The criteria used to separate the three Kco periods (increasing, peak, decreasing) was based partially on the number of data points with a Kco value above one and partially due to personal judgment because of the pattern of the data points. With the 1980 Rogers Farm data, the points were all daily values, which were an average of three populations. Here it was decided to use the criteria of three points above a value of one as acknowledging that potential ET or that the peak Kco period has been reached. A similar analysis was used to separate the peak crop coefficient period from the decreasing Kco period. The value for peak Kco is an average of the data points within the Kco peak period.

1981 Rogers Farm. Predicting the crop coefficient using the dimensionless, fraction of total cumulative 50-90 stress GDD as the independent parameter was tested with different maturity lengths of corn at the Rogers Farm in 1981. Experiments were conducted using six different corn varieties with nominal maturity lengths of 80, 85, 100, 105, 120, and 140 days.

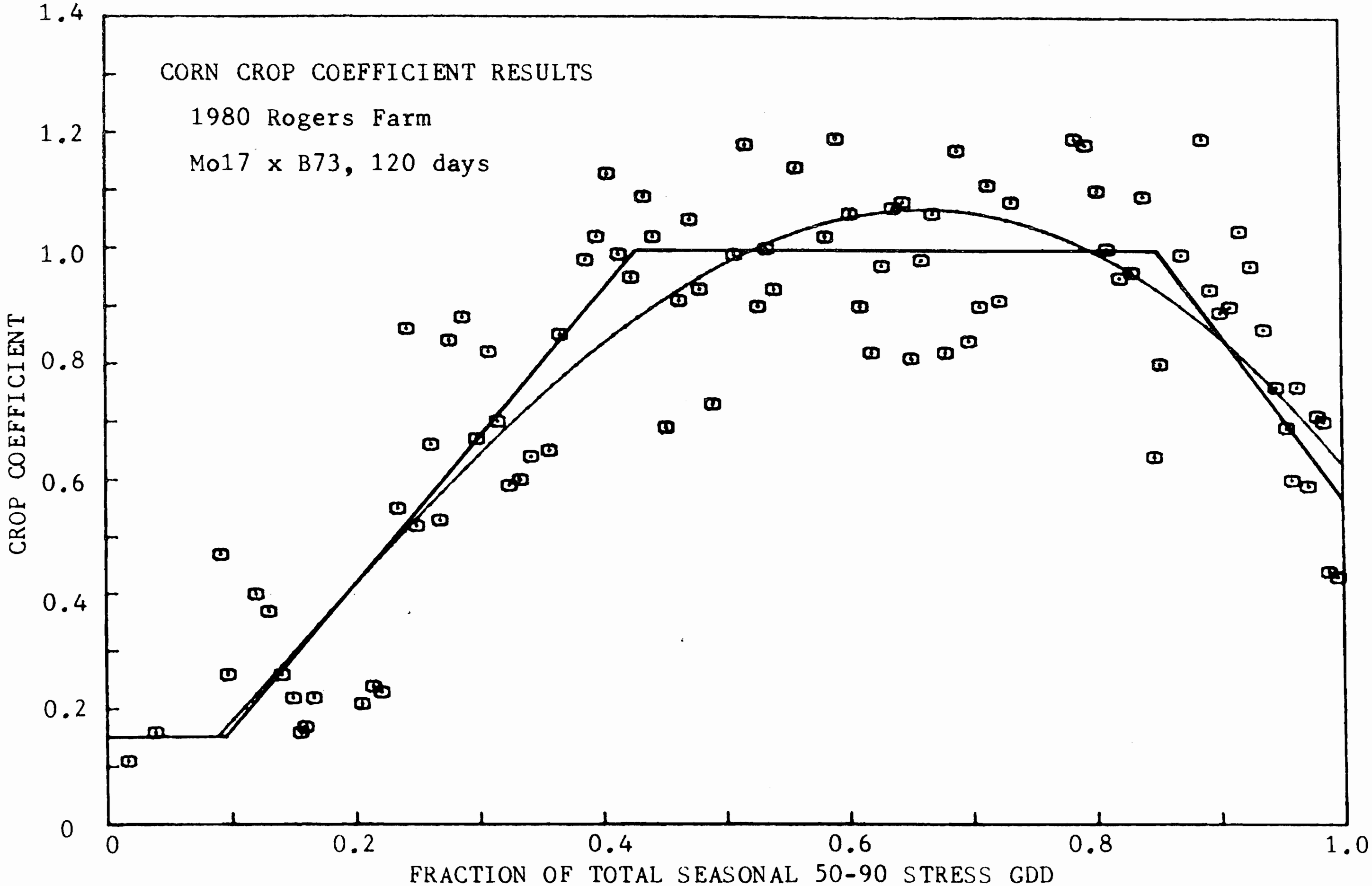

Figure 18. Corn crop coefficient results for Mo17 x B73 at the Rogers Farm during 1980.

Table 9. Regression coefficients for the corn crop coefficients from the Rogers Farm.[1]

Linear Model

Year	Variety	e	a	b	c	d	Corr. Coef.
1980	All	0.15	-0.088	2.532	0.10	0.43	0.81
1981	All except VAR120	0.15	-0.290	3.014	0.15	0.45	0.81
Both	All except VAR120	0.15	-0.183	2.724	0.12	0.45	0.79

Year	Variety	f	g	h	p	q	Corr. Coef.
1980	All	1.00	3.444	-2.880	0.85	1.00	0.71
1981	All	1.07	3.570	-3.094	0.81	1.00	0.58
Both	All	1.05	3.459	-2.955	0.82	1.00	0.58

Polynomial Model

Year	Variety	F	r	s	Corr. Coef.
1980	All	0.15	0.09	1.00	0.82
1981	All without VAR120	0.15	0.12	1.00	0.78
Both	All withouth VAR120	0.15	0.11	1.00	0.78

Year	Variety	A	B	C	D	E
1980	All	-0.0469	2.133	1.819	- 4.745	1.465
1981	All without VAR120	0.0265	-0.0435	11.195	-17.422	6.716
Both	All without VAR120	0.0240	0.262	9.931	-16.079	6.406

[1] Independent variable is fraction of seasonal 50-90 stress GDD. Linear model is described by equations 4-7, polynomial model is described by equation 8-9.

Polynomial equations for the six varieties as a function of cumulative 50-90 stress GDD and fraction of total seasonal 50-90 stress GDD are shown in Figures 19 and 20, respectively. The difference in the number of GDD necessary to reach maturity is very evident in Figure 19. When the crop coefficient equations are based on fraction of total cumulative GDD, the equations for different maturity lengths of corn are quite similar (Figure 20).

Coefficients for both the polynomial and linear models were found for each of the six varieties grown in 1981 at the Rogers Farm and are given in the Appendix along with figures showing the Kco relationships.

The number of data points for each variety in 1981 are fewer than those available in 1980 because of fewer replications of each variety and adverse weather conditions in 1981. In 1981, the ET of each of the six varieties was measured with only one lysimeter per variety. Consequently, two day values of ET and ETp were used to determine the Kco values to reduce the scatter of the data points. Also, considerable rain fell during the latter half of the 1981 growing season. Consequently, individual problems with some lysimeters during this period caused more values to be deleted from some of the data sets.

A more lenient criteria was used for separating the Kco increasing, peak, and decreasing periods for the six varieties at the Rogers Farm in 1981. Generally, two data points above a Kco value of one was used to separate the three Kco periods.

Crop coefficient values for the peak period for the six different varieties in 1981 were higher than the average value in 1981. The peak ET values were 1.01, 1.08, 1.02, 1.07, 1.08, and 1.13 for the 80, 85, 100, 105, 120, and 140 day maturity corn varieties, respectively. The overall avaerage for the Rogers Farm in 1981 was 1.07 and the overall Rogers Farm average was 1.05 for both years.

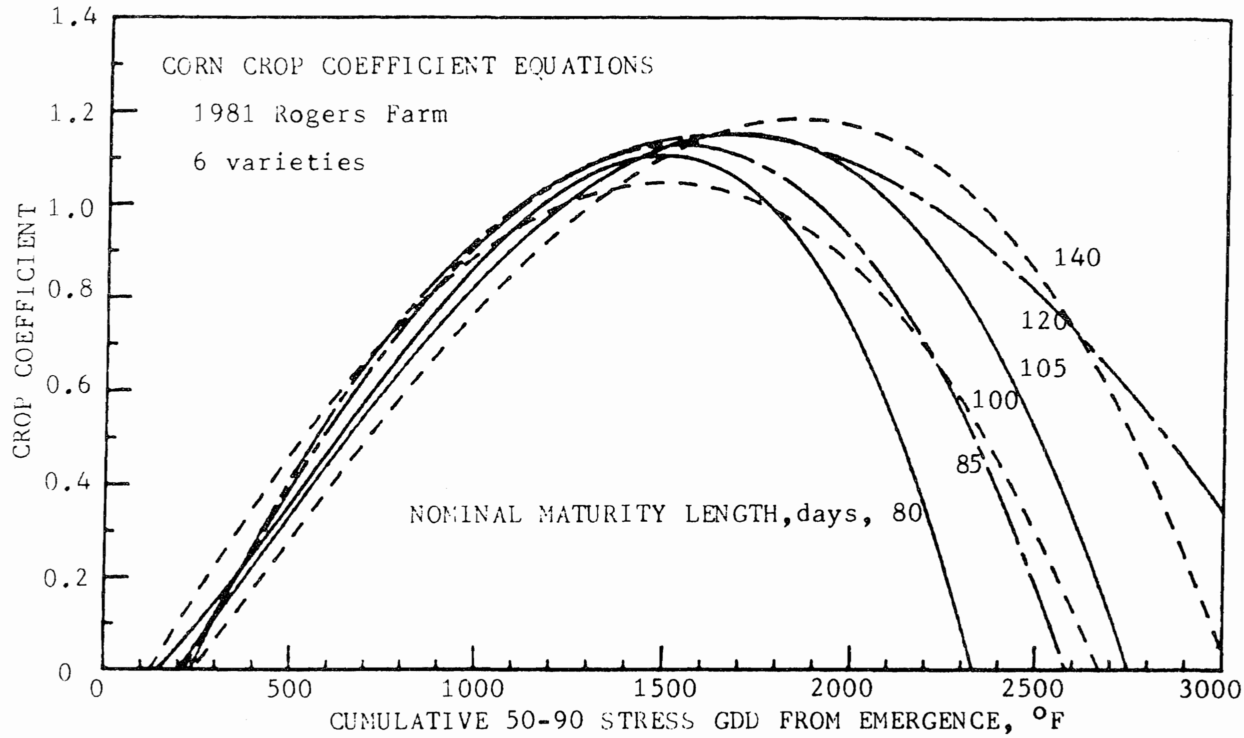

Figure 19. **Corn crop coefficient equations as a function of GDD for six varieties at the Rogers Farm during 1981.**

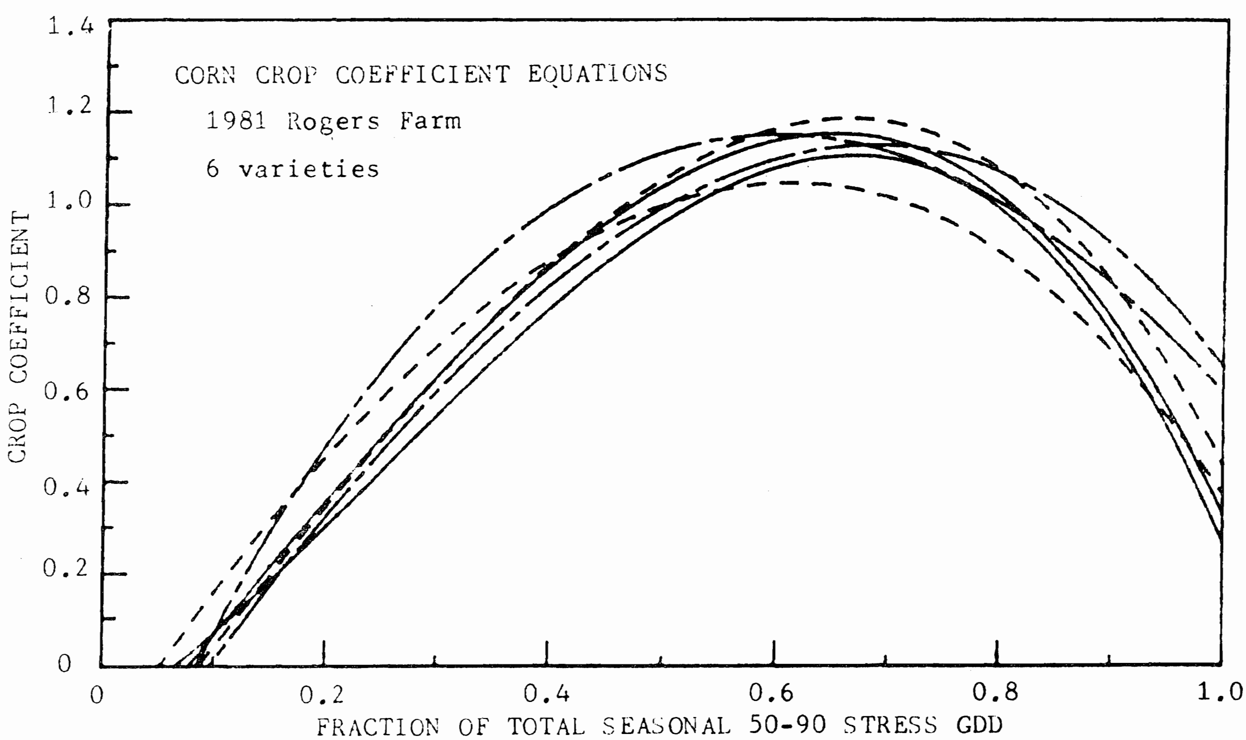

Figure 20. **Corn crop coefficient equations as a function of fraction of total seasonal GDD for six varieties at the Rogers Farm during 1981.**

The six varieties with different maturity lengths had vastly dissimilar amounts of total ET and GDD, as is shown in Table 10. The 120 day variety, M107 x B73 had less than one percent difference in both total GDD and total ET between 1980 and 1981 (Table 10) yet 1980 and 1981 were dissimilar with respect to temperature and precipitation. Temperature levels at Rogers Farm were quite different between 1980 and 1981. Temperatures were above normal during 1980 with 3030 no limit GDD accumulated from May 20 through September 15, as compared to a 30 year average of 2857 GDD. Conversely, 1981 was much cooler than normal with 2632 no limit GDD for the same period. Consequently, the varieties in 1981 required more actual days to mature than their rated maturity length. The 140 day variety did develop a black layer, but its maturity was probably induced by declining minimum temperatures.

Combining all the linear crop coefficient equations for the Rogers Farm during 1981 shows good similarity among the six varieties (Figure 21). However, the one exception is VAR120 which has a larger slope and hence, predicts a value of 1.0 much sooner than the other linear equations. This was partially due to that variety developing a larger LAI sooner than the other varieties.

Overall linear and polynomial regression results for the Rogers Farm in 1981 are given in Table 9. The overall linear regression for the increasing Kco data does not include VAR120 because of its dissimilarity from the other five varieties. However, VAR120 is included in the overall Kco decreasing equation.

The fourth order polynomial is also shown in Figure 21. The polynomial equation peaks at 1.14 while the overall average is 1.07 for the peak period data points. The polynomial equation underpredicts the time when the crop coefficient value should reach a value of one. This again tends to show that the linear equations better represent the crop coefficient relationship.

Table 10. Rated maturity length, total GDD, and total ET for the season for the corn varieties grown at the Rogers Farm.

Year	Rated Maturity Length days	Actual Maturity Length days	Total 50- * GDD 1	Total 50-86 GDD	Total 50-90° Stress GDD	Total Seasonal Crop ET (cm)
1980	120	120	3076	2806	2776	69.1
1981	80	101	2336	2224	2233	55.5
	85	101	2336	2224	2233	54.8
	100	113	2553	2441	2450	58.2
	105	124	2704	2589	2600	62.2
	120	135	2856	2739	2752	68.4
	140	141	2901	2784	2797	70.7

1 No upper temperature limit.

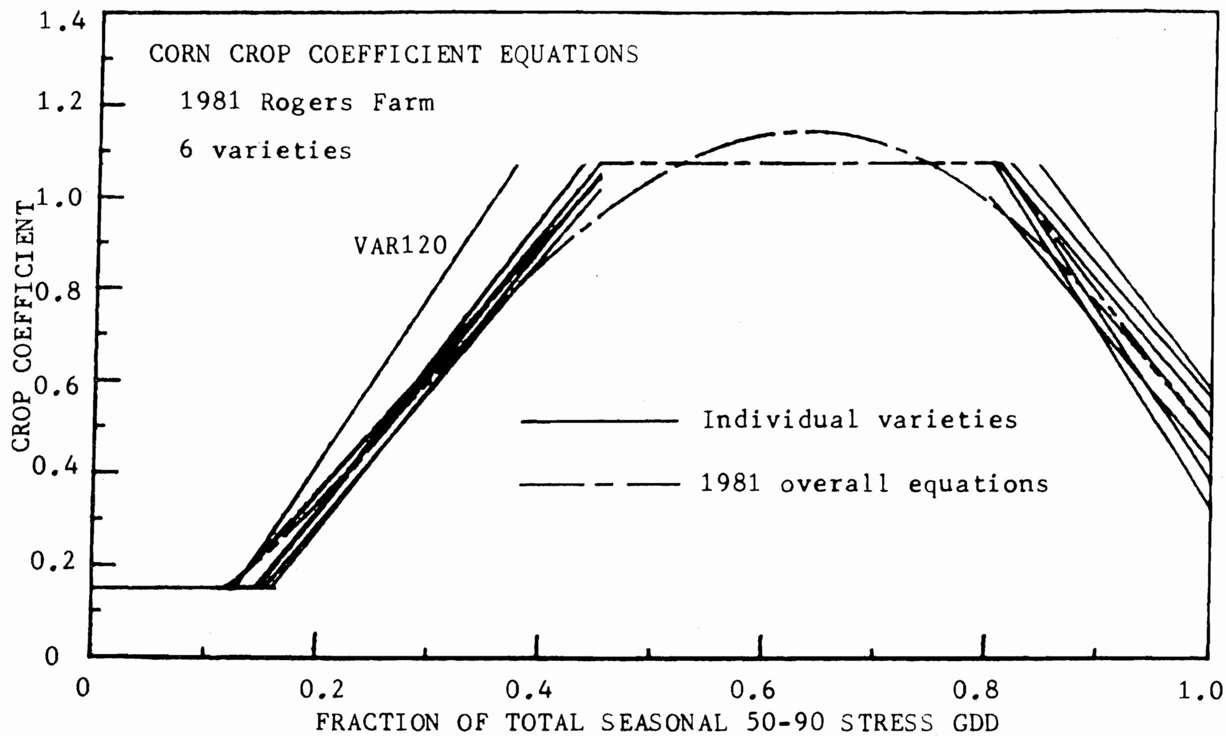

Figure 21. Overall corn crop coefficient equations for six different maturity varieties at the Rogers Farm during 1981.

The LAI results from the Rogers Farm during 1981 for the different maturity corn varieties help to explain the ET and Kco results. The LAI results for the Rogers Farm as a function of time and as a function of cumulative GDD from emergence are shown in Figures 22 and 23, respectively. The six varieties at the Rogers Farm, all at a population of 77500 pl/ha (31363 pl/ac), showed little difference of increasing LAI among the various plant populations. However, there is substantial difference in the level and duration of peak LAI among the varieties. Since population is constant, all varieties essentially accumulate leaf area in a similar fashion. However, the varieties vary in the number of leaves they develop, ranging from 15 to 22 leaves, which causes the differences in duration of peak LAI. The difference in seasonal ET among the varieties, as shown in Table 10, is primarily due to the difference in maturity length of the varieties.

The 80 day maturity variety did not reach the 2.7 threshold LAI value (Figures 22 and 23). The average of the peak Kco values for this variety was 1.01, the lowest of the six varieties.

Overall Rogers Farm. The overall 1981 Rogers Farm crop coefficient equations are fairly similar to the 1980 Rogers Farm equations (Figure 24). However, the 1980 increasing linear equation predicts Kco values up to 0.15 larger near the beginning of the season than the same equation for 1981. The main differences in the polynomial equations occurs during the middle of the season, due to the difference in the average value of the peak period between the two years. Overall, linear and polynomial regession results for the Rogers Farm for both years are given in Table 9.

Sandhills Ag Lab. In order to further test the nondimensional fraction of total cumulative GDD parameter, an analysis was done on lysimetric measured ET data from SAL for three years. Crop coefficient values and equations were found

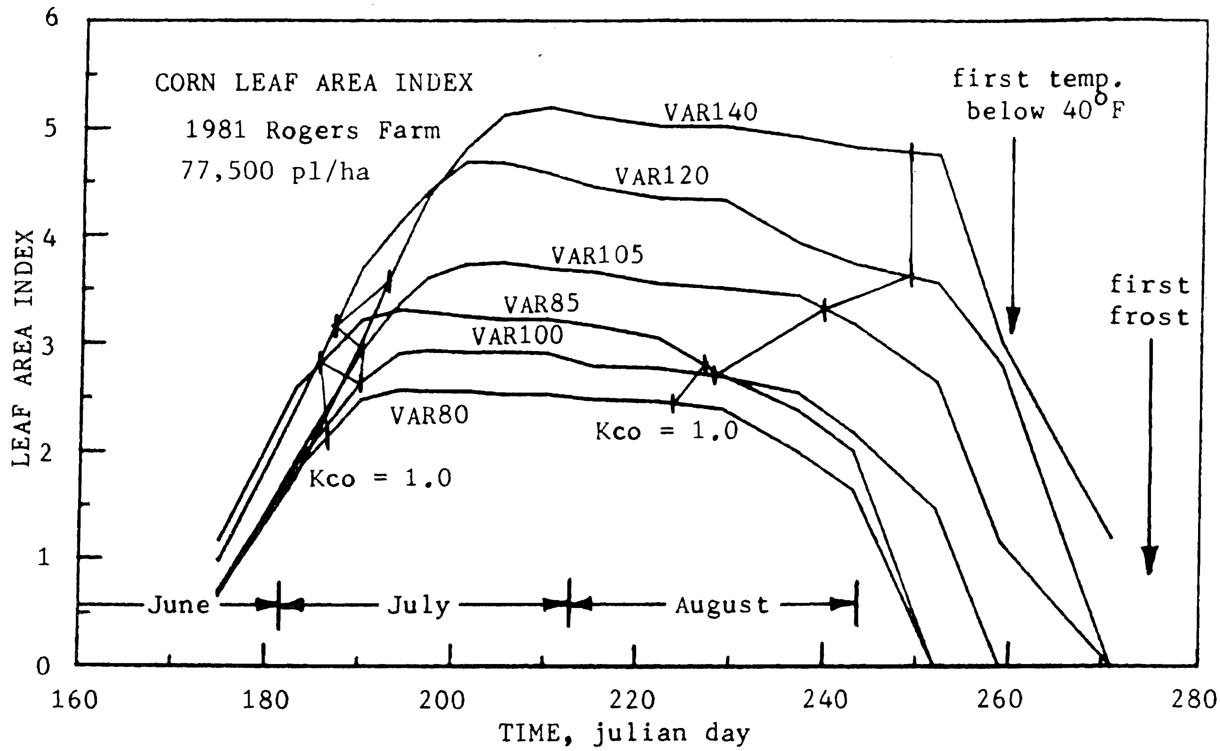

Figure 22. Corn leaf area index values versus time for six different maturity varieties at the Rogers Farm during 1981.

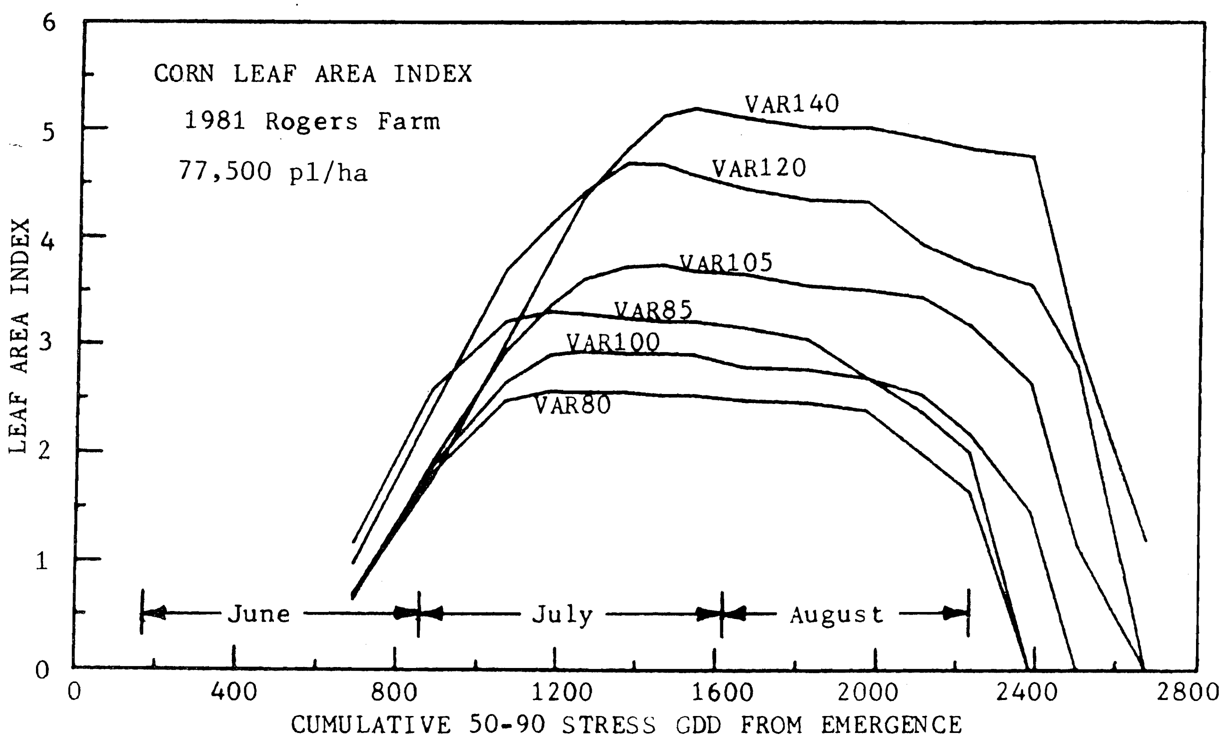

Figure 23. Corn leaf area index values versus cumulative GDD for six different maturity varieties at the Rogers Farm during 1981.

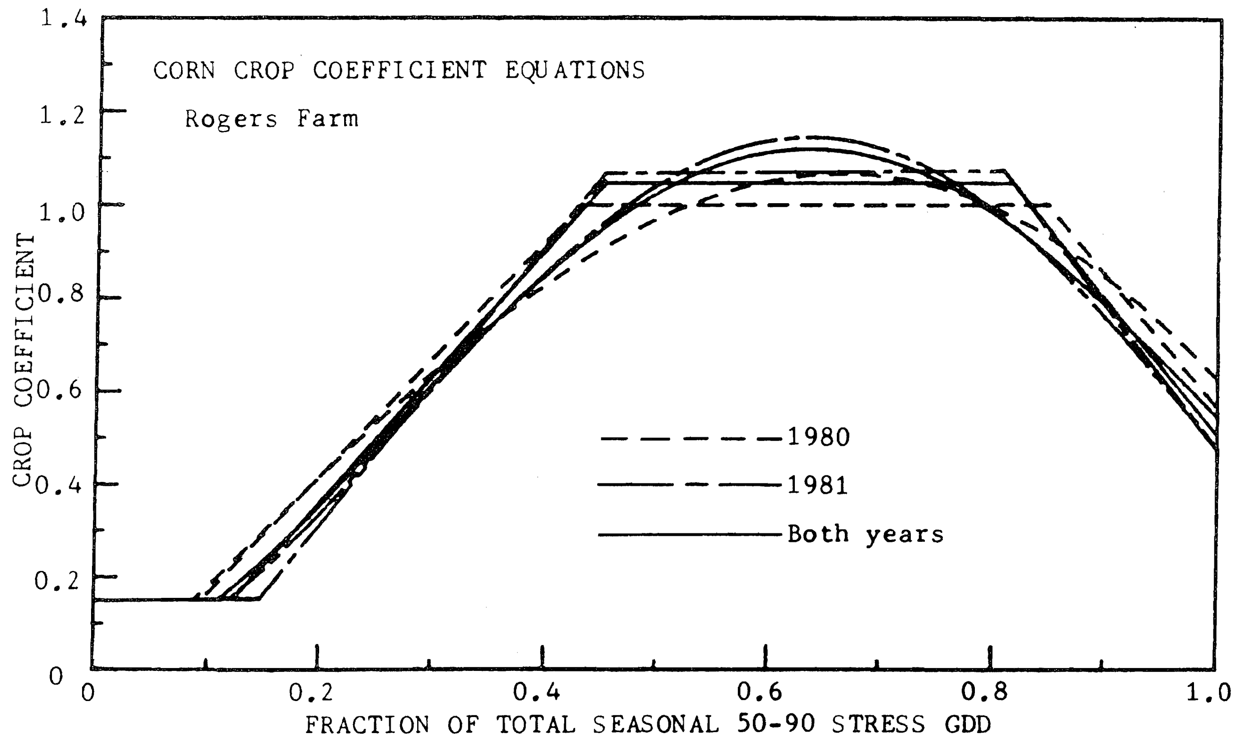

Figure 24. Overall corn crop coefficient equations for the Rogers Farm for 1980 and 1981.

from SAL data for VAR105, VAR110, and VAR120 in 1981, VAR120 in 1980, and VAR100 in 1978. Linear and polynominal equations and the data points for SAL are shown in Figures 25 through 30. Early season data points in 1978 and 1980 were missing, so increasing linear and polynomial equations were not found for those years.

The crop coefficient data in 1981 are two day averages since there was only one replication (one lysimeter) of each variety. However, the data points for SAL in 1978 and 1980 are daily Kco values because they are an average of four replications of different populations. The different populations showed no significant difference in total seasonal ET.

The criteria used to separate the Kco increasking, peak and decreasing periods was similar to as that used at the Rogers Farm in 1981. The existance of two data points with a Kco value or more generally terminated the end of the Kco increasing or decreasing periods. However, missing data or excessive scatter in the data sometimes altered the criteria.

The regression results of Kco versus fraction of total cumulative 50-90 stress GDD for the three varieties during 1981 are given in Table 11. The peak Kco values at SAL for 1978 and 1980 were also generally lower and more variable than the 1981 Rogers Farm results. The overall average peak Kco value was 0.98 for 1980-81 at SAL and was 0.99 for all three years at SAL. The overall corn coefficients from the experiments at SAL are shown in Figure 30.

The LAI results from SAL during 1981 are shown in Figures 31 and 32. A minimum temperature of 31°F (-0.6°C) on September 15th apparently did not kill the plant growth since green leaf area continued into October. No other freezing temperatures were recorded until October 5th, when all measurements were stopped.

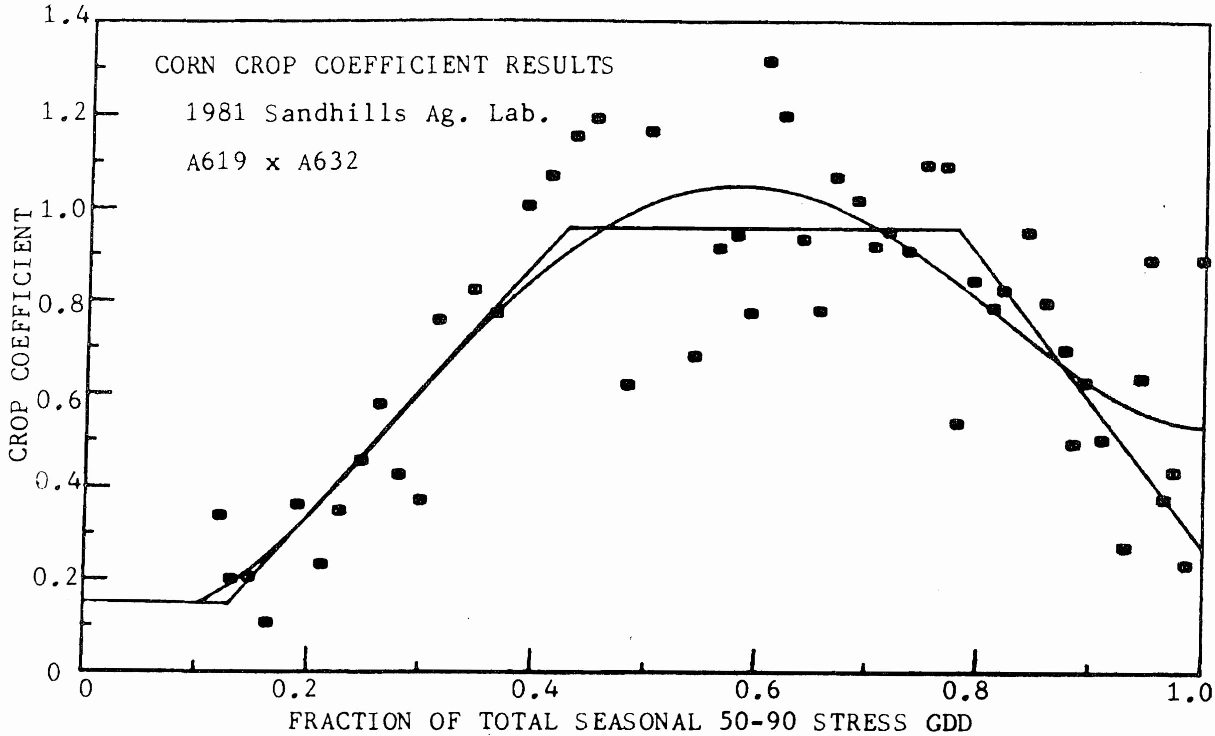

Figure 25. Corn crop coefficient results for a 105 day maturity variety at the Sandhills Ag. Lab. during 1981.

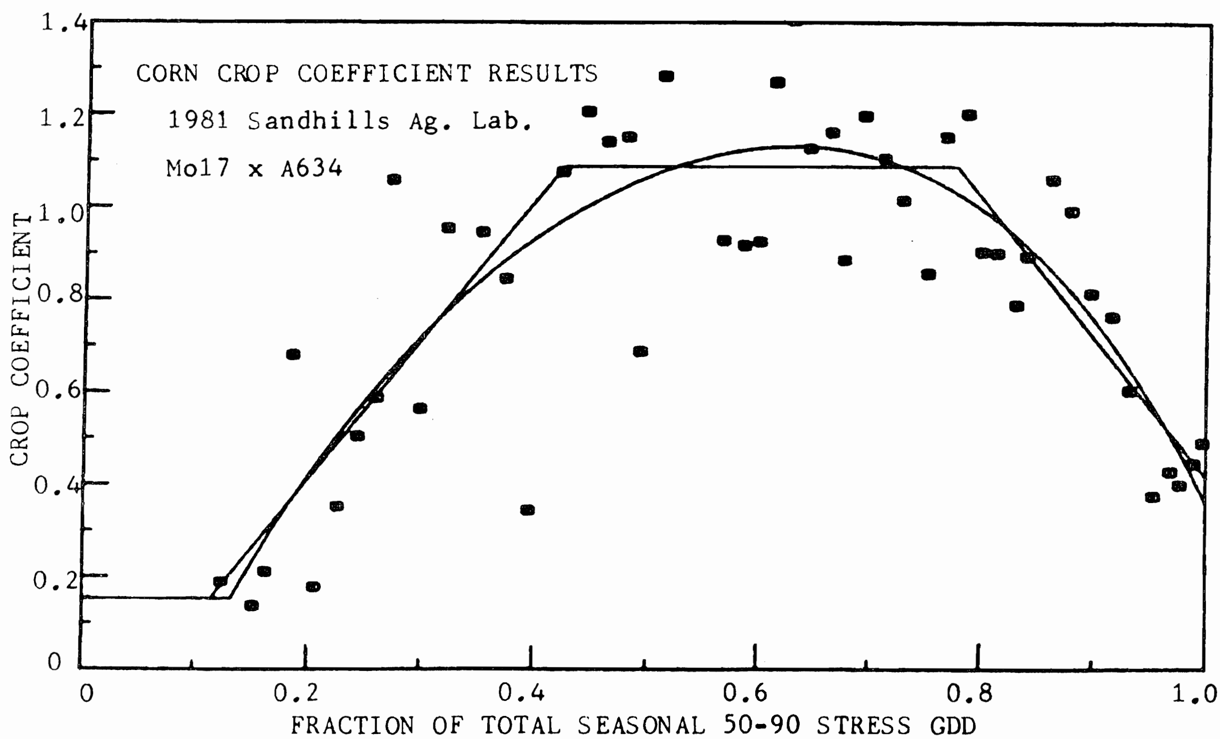

Figure 26. Corn crop coefficient results for a 110 day maturity variety at the Sandhills Ag. Lab. during 1981.

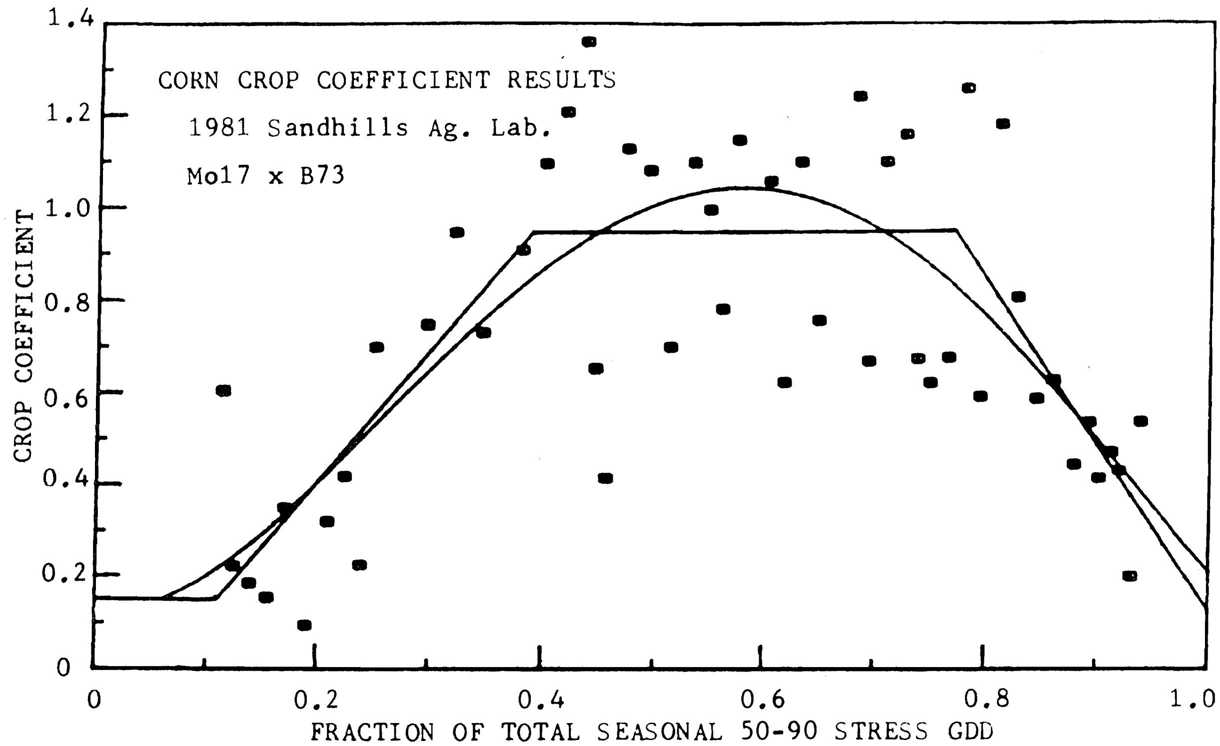

Figure 27. Corn crop coefficient results for a 120 day maturity variety at the Sandhills Ag. Lab. during 1981.

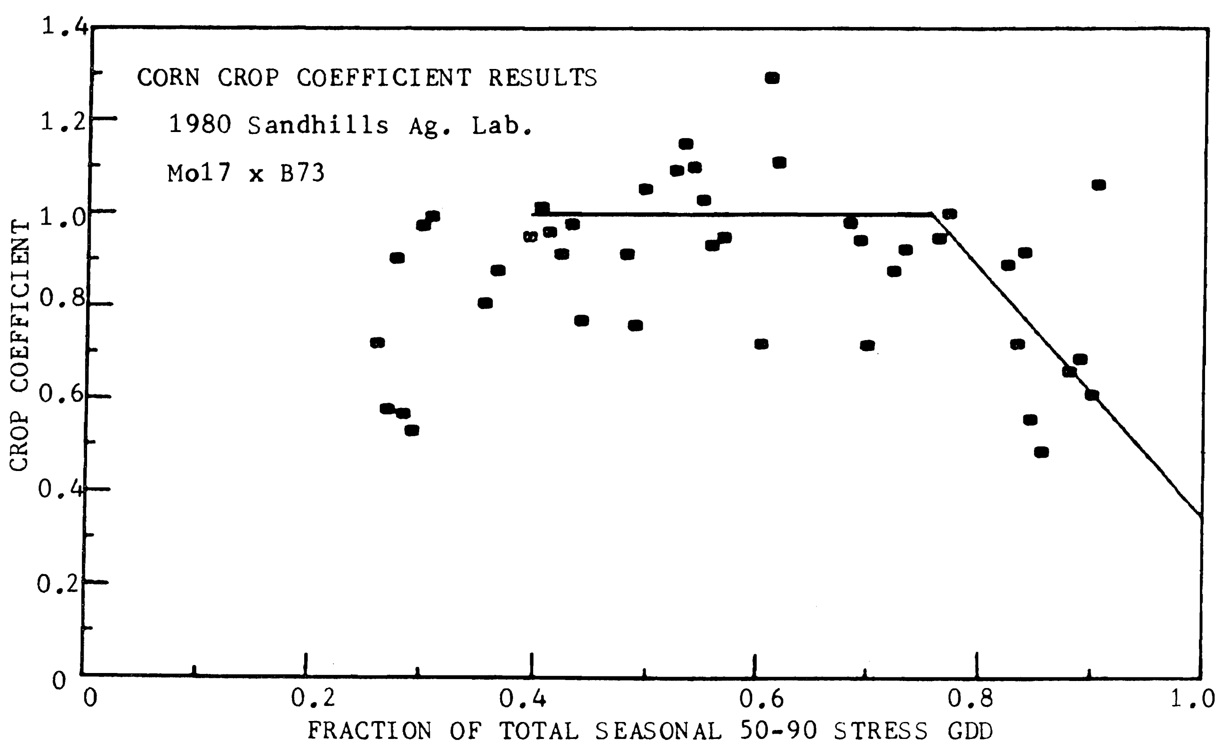

Figure 28. Corn crop coefficient results for a 120 day maturity variety at the Sandhills Ag. Lab. during 1980

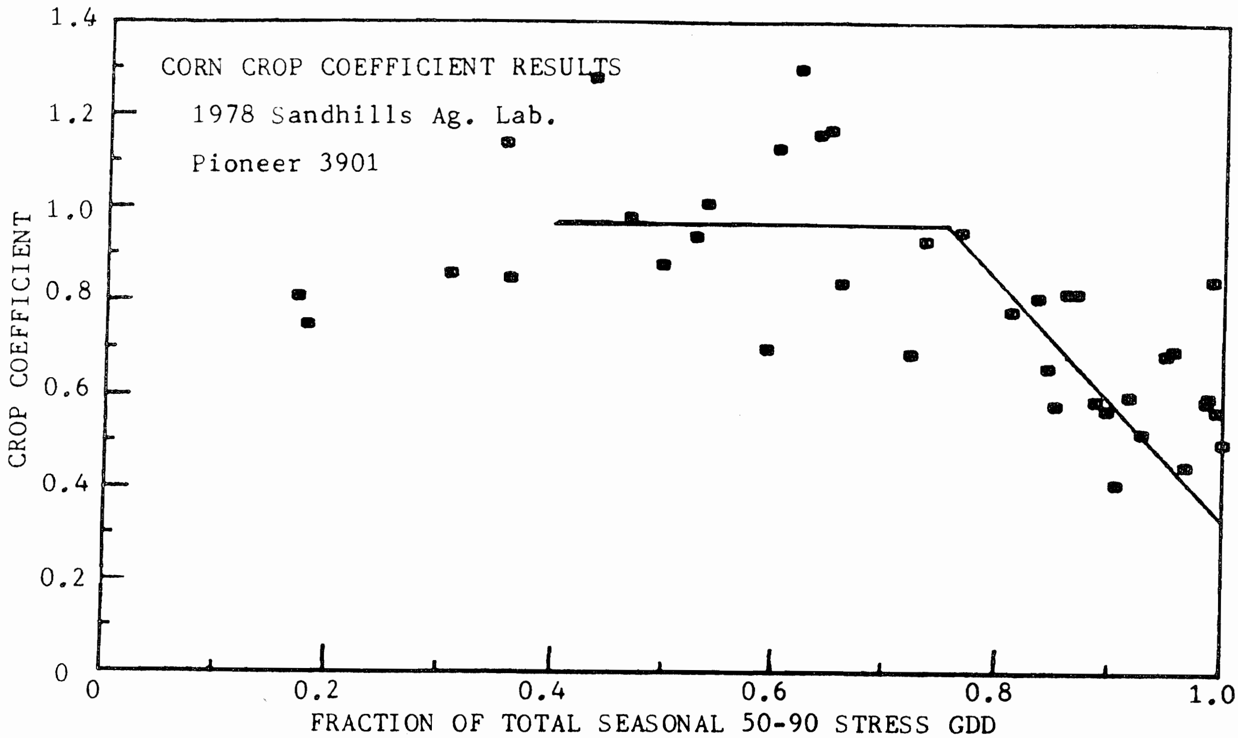

Figure 29. Corn crop coefficient results for a 100 day maturity variety at the Sandhills Ag. Lab. during 1978.

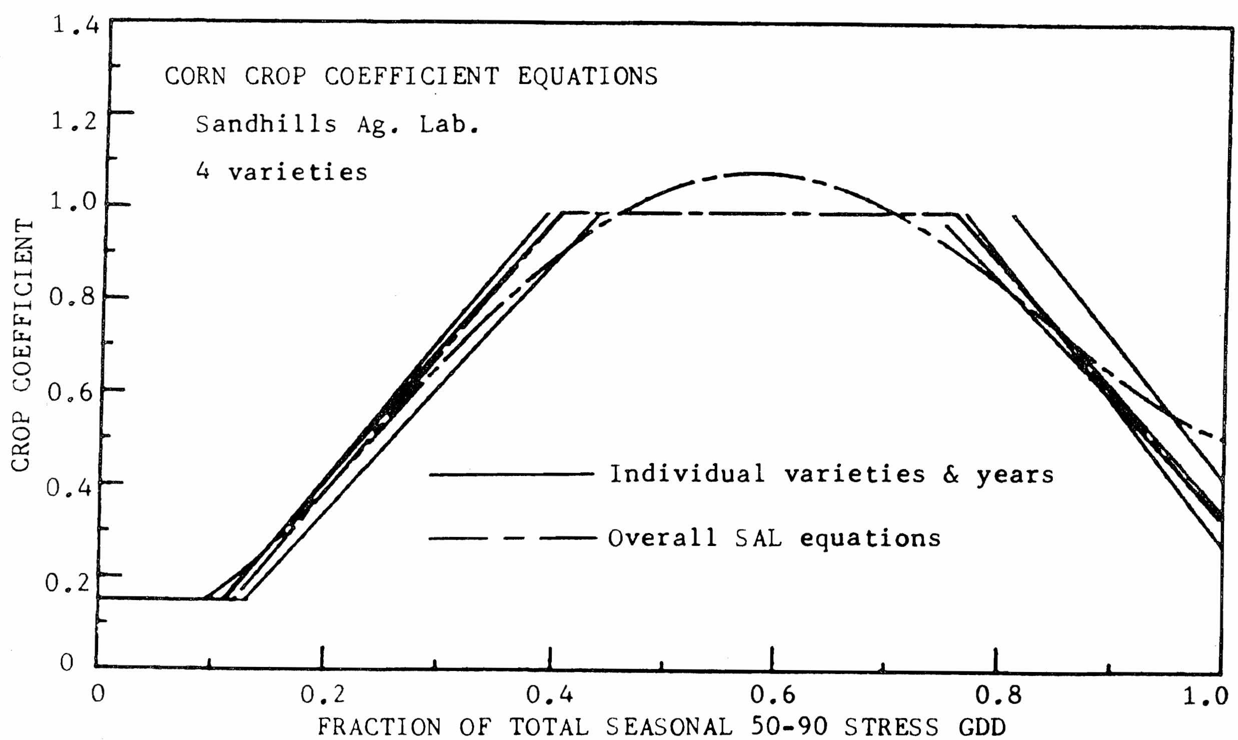

Figure 30. Overall corn crop coefficient equations for the Sandhills Ag. Lab.

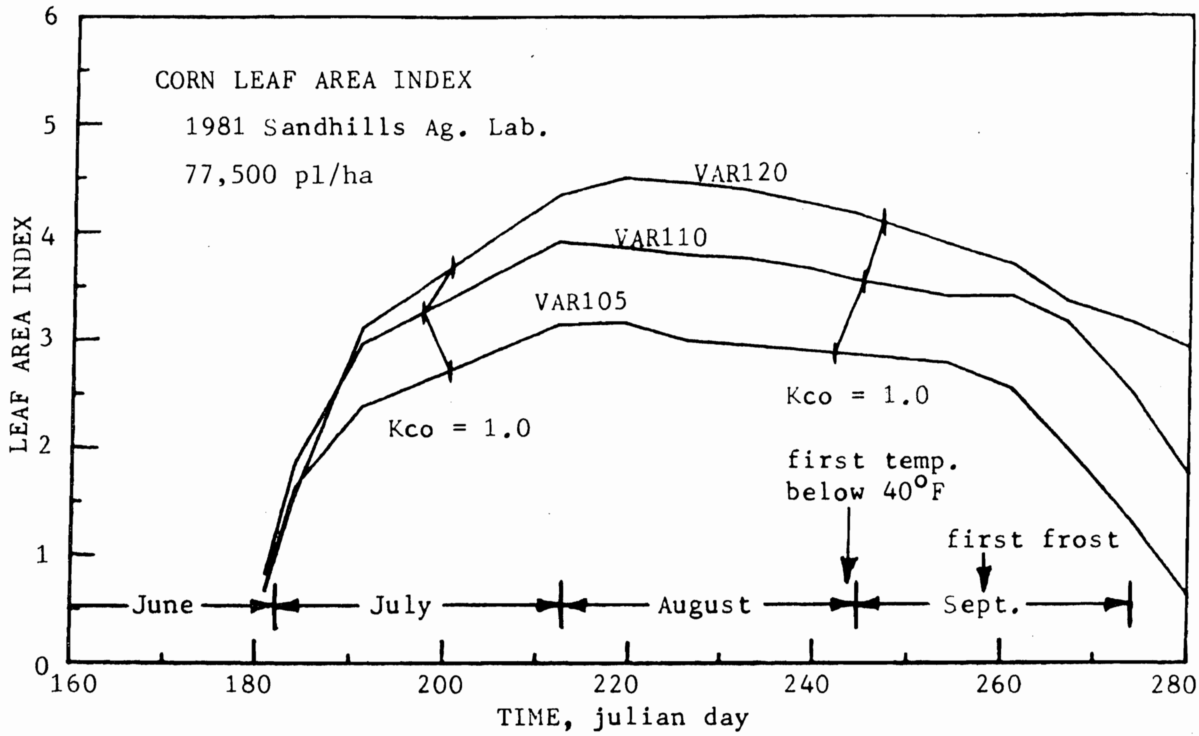

Figure 31. Corn leaf area index values versus time for three different maturity varieties at the Sandhills Ag. Lab. during 1981.

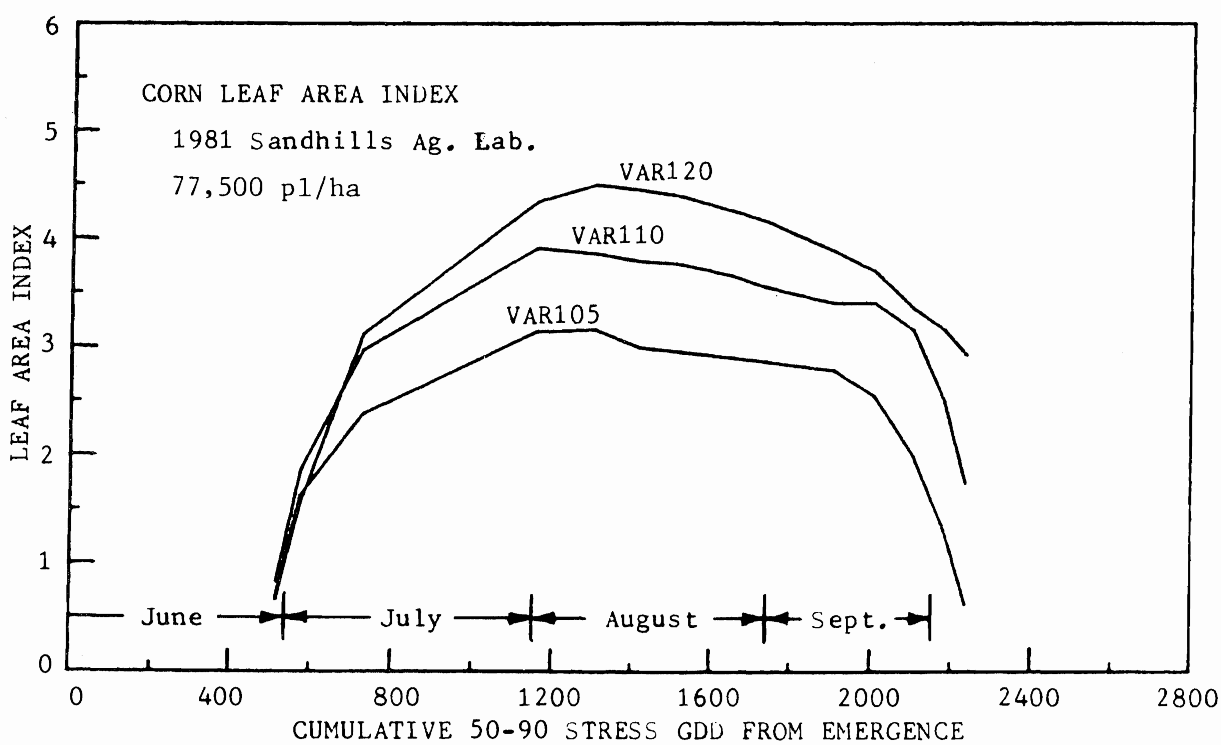

Figure 32. Corn leaf area index values versus cumulative GDD for three different maturity varieties at the Sandhills Ag. Lab. during 1981.

Table 11. Regression coefficients for the corn crop coefficients from SAL. [1]

Linear Model

Year	Variety	e	a	b	c	d	Corr. Coef.
1981	VAR105	0.15	-0.2036	2.719	0.13	0.43	0.783
	VAR110	0.15	-0.1870	3.000	0.11	0.43	0.798
	VAR120	0.15	-0.1648	2.859	0.11	0.39	0.672
	ALL	0.15	-0.2043	2.948	0.12	0.40	0.763

Year	Variety	f	g	h	p	q	Corr. Coef.
1981	VAR105	0.96	3.371	-3.091	0.78	1.00	0.742
	VAR110	1.09	3.424	-3.009	0.78	1.00	0.728
	VAR120	0.94	3.720	-3.595	0.77	1.00	0.513
1980	VAR120	0.96	3.020	-2.676	0.77	1.00	0.689
	VAR100	1.04	2.867	-2.534	0.72	1.00	0.689
BOTH	ALL	0.99	3.090	-2.767	0.76	1.00	0.553

Polynomial Model

Year	Variety	F	r	s	Corr. Coef.
1981	VAR105	0.15	0.10	1.00	0.664
	VAR110	0.15	0.13	1.00	0.701
	VAR120	0.15	0.06	1.00	0.566
	ALL	0.15	0.10	1.00	0.584

Year	Variety	A	B	C	D	E
1981	VAR105	0.1664	-1.776	18.763	-30.729	14.106
	VAR110	-0.5416	6.357	-9.084	7.577	-3.947
	VAR120	0.1269	-0.271	11.987	-20.037	8.401
	ALL	0.0860	-0.438	14.162	-24.569	11.264

[1] Independent variable is fraction of total cumulative 50-90 stress GDD. Linear model is described by equation 4-7, polynomial model is described by equations 8-9.

Overall SAL & Rogers Farm. A comparison of the crop coefficient results from both SAL and Rogers Farm is given in Figure 33 which shows good similarity during the Kco increasing time period. However, there is a difference in the decreasing linear equation between locations. The regression coefficients for the combined crop coefficient are given in Table 12.

The peak value of the fourth order polynomial is 1.10 and the overall average of the peak Kco values is 1.02 for all years and both loccations. Again, the polynomial overpredicts at the peak period and underpredicts where the linear equations intersect. Integration of the polynomial model over the season equals 0.714 and integration of the linear equations equal 0.716. Thus, there is little difference in seasonal ET between the two models; however, this is a considerable difference in the distribution of crop ET during the season.

The difference in the crop coefficients developed at the Rogers Farm and SAL can be partially explained by the following analysis. Time, GDD, LAI, and stage of growth data for the times that Kco reaches and declines from a value of one at both locations are tabulated in Table 13. These times were determined from the respective linear increasing and decreasing Kco equations for each variety at each location. Apparently, if shorter season varieties are planted in a region with a relatively long season, the peak Kco period tends to start and end at LAI values more closer to the threshold 2.7 value. The peak period also appears to be more closely associated with stage of growth, especially at the time that peak Kco period ends. The four varieties with the shortest maturity length at the Rogers Farm begin the peak Kco period near an average stage of growth value of 4.2 (tassle emergence). This particular growth stage may not be significant due to the modification of Hanways vegetative scale to accommodate varieties with different total leaf numbers. However, these same four varieties all end their peak Kco periods near stage 9.1, just after full kernel dent.

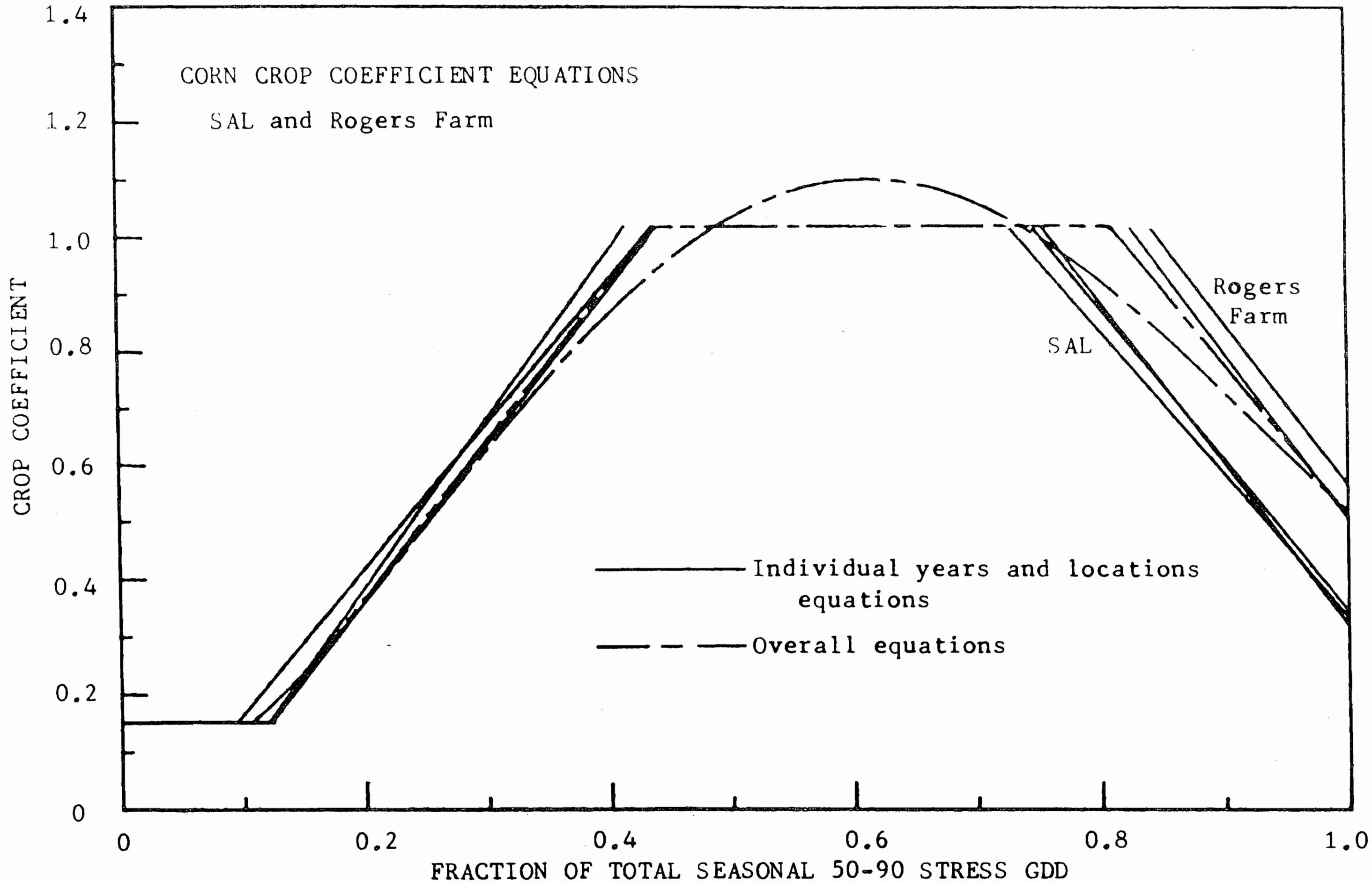

Figure 33. Overall corn crop coefficient equations for the Rogers Farm and the Sandhills Ag. Lab.

Table 12. Regression coefficients for the corn crop coefficient combined for all sites and all years. [1]

Linear Model

Variety	e	a	b	c	d	Corr. Coef.
Linear Model						
ALL	0.15	-0.180	2.738	0.12	0.44	0.767

Variety	f	g	h	p	q	Corr. Coef.
ALL	1.02	3.208	-2.698	0.81	1.00	0.525

Polynomial Model

Variety	F	r	s	Corr. Coef.
ALL	0.15	0.10	1.00	0.710

Variety	A	B	C	D	E
ALL	0.0447	-0.0349	11.592	-19.210	8.126

[1] Independent variable is fraction of total cumulative 50-90 stress GDD. Linear model is described by equations 4-7, polunomial model is described by equations 8-9.

Table 13. Values of corn growth parameters for both locations during 1981 at the beginning and end of the Kco peak period.

Nominal Maturity Length	Calendar Day	Cumulative 50-90 Stress GDD	Fraction of Seasonal GDD	Leaf Area Index		Stage of Growth	
Kco reaches 1.0 value at the Rogers Farm							
80	187	991	0.444	2.2		4.7	
85	186	967	0.433	2.9	Ave.	3.8	Ave.
100	190	1063	0.434	2.6	2.7	4.2	4.2
105	191	1105	0.425	3.0		4.2	
120	187	980	0.356	3.1		3.0	
140	193	1152	0.412	3.6		3.3	
Average	190	1056	0.431				
Kco reaches 1.0 value at SAL							
105	201	967	0.443	2.8		4.4	
110	198	885	0.396	3.3		3.9	
120	201	962	0.407	3.7		3.7	
Kco declines from 1.0 at the Rogers Farm							
80	223	1836	0.822	2.4		9.1	
85	227	1934	0.866	2.8	Ave.	9.1	Ave.
100	228	1960	0.800	2.7	2.8	8.8	9.1
105	240	2158	0.830	3.3		9.3	
120	249	2325	0.845	3.6		8.5	
140	249	2331	0.833	4.7		8.1	
Kco declines from 1.0 at SAL							
105	242	1708	0.764	2.9		7.8	
110	245	1760	0.806	3.5		7.9	
120	247	1787	0.756	4.0		7.2	

The shortest season variety grown at SAL appears to have these same characteristics with LAI value of 2.8 and 2.9, at the beginning and end of its Kco period. However, this was because its peak LAI was never much greater than these values and not because of the short maturity effects exhibited at the Rogers Farm. It ends its Kco peak period at stage 7.8, much sooner than the 9.1 average value at the Rogers Farm, where season length was not limited.

All three varieties at SAL appear to have ended their Kco peak periods when minimum temperatures dropped below 40°F (4.4°C) (Figure 31). Stage of growth at this time for the three varieties ranged from 7.2 to 7.9, medium to hard dough, and was sooner than even the later maturity varities at the Rogers Farm ended their Kco peak periods. The three varieties at SAL, however, maintained their peak leaf area for two or more weeks, and did not start to decline significantly until after the first frost. These temperature effects seem to have had no bearing on the results at the Rogers Farm because leaf area started to decline long before minimum temperatures dropped below 40°F (Figure 22).

Since the varieties at SAL end their peak Kco periods much sooner, their equations naturally have a larger intercept but yet have a similar slope, as is shown in Figure 33. This difference may be almost entirely due to the relative maturity effects as just discussed. The true overall Kco decreasing equation for SAL may in fact be quite similar to the overall equation from the Rogers Farm.

<u>Overall results compared to the Jensen equations</u>. Crop coefficient equations have been developed for a number of different crops by Jensen (1969), Jensen et al. (1970), and Jensen et al. (1971). These equations were found from data taken at a number of locations in semiarid regions and are presented by Kincaid and Heermann (1974).

The overall linear Kco equations for SAL and the Rogers Farm for the different varieties are compared to the corn crop coefficient equations developed by Jensen and others in Figure 34. The crop coefficient and leaf area results show there is little difference between varieties for the time period before effective full cover. However, there was a difference in the duration of the peak Kco period. Therefore, one equation was found for all varieties for the time period before effective full cover. However, due to the difference in duration of the Kco peak period, equations were developed for each variety for the period after effective full cover.

The value of fraction of total seasonal GDD of the overall linear Kco increasing equation with a Kco value of 1.0 was used to find the GDD at effective full cover for each variety. These GDD values ranged from 962 to 1206 with an average of 1082 which occurred on julian day 191 or July 10th. All varieties were planted on calendar day 127 or May 7th. From these results, time values were found for every one tenth increment of increasing Kco and are shown in Figure 34.

The values predicted by the overall linear crop coefficient equation before effective cover are significantly lower than those values predicted by the Jensen equation. However, values presented by Wright (1982) are more similar to those values obtained at the Rogers Farm. The revised values found by Wright are form lysimeter measurements and incorporate improved techniques for finding basal, dry soil surface, ET values.

The six varieties grown at the Rogers Farm during 1981 are represented by different lines for the period of days after effective full cover due to differences in the duration of the peak Kco period. Both early season varieties at the Rogers Farm during 1981 matured at the same time, so both are represented by the same line.

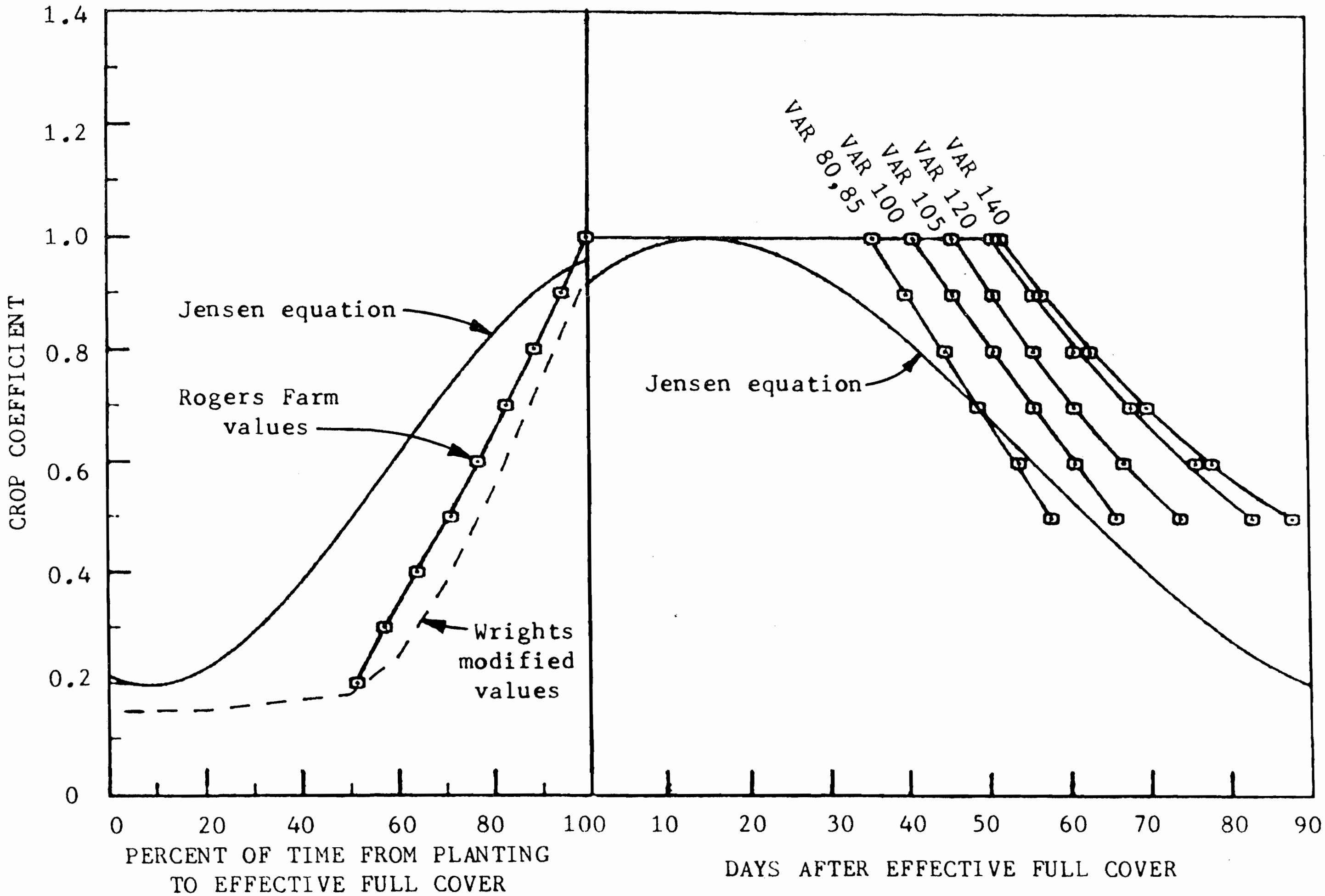

Figure 34. Comparison of the Rogers Farm crop coefficient results to Jensens equations for corn and Wrights modified values.

The two short season varieties compare fairly well with the Jensen equation for the period after effective full cover. However, there is significant dissimilarity between the two lines where Kco begins to decrease. Much of this dissimilarity can be expected due to the problem with using polynomials to represent the Kco data. Elsewhere, the two lines do not differ greatly.

The other varieties, VAR100, VAR105, VAR120 and VAR140, all have progressively longer peak Kco periods and subsequently, different Kco decreasing lines are necessary for each variety. Furthermore, the Kco decreasing lines became less linear and more parallel to Jensen's equation with increased maturity length.

Relative maturity length within a region seems to have an effect on the shape of the Kco decreasing line when represented by time. The long maturity varieties at the Rogers Farm have non-linear Kco decreasing lines because the cooler fall weather required more time to acquire the latter GDD to bring about senescence. This was not true with the two shorter season varieties, which both matured August 31st, long before temperature became a factor to effect senescence.

The Jensen equation after effective full cover appears to represent a short season variety because of its short peak Kco period but yet a variety that is relatively long for the region it was grown in because of the shape of the Kco decreasing line. This is essentially true on both notes because the Jensen corn Kco equations were developed from data obtained near Kimberly, Idaho. If the crop coefficient data from SAL were plotted on Figure 34, they would probably be very similar to the curve shown for the Jensen equation.

The additional time required to reach effective full cover for a cool region can influence dissimilarities among the Kco decreasing equations. If a cool region requires more time to reach effective full cover, then the effective full cover date for a cool region would occur later than for a warm region. This reduces the peak Kco period. The cooler region has fewer days after effective full cover before senescence occurs.

Stage of Growth. Utilizing the linear relationship between stage of growth and growing degree days, a crop coefficient was developed as a function of stage of growth and is shown in Figure 35. Because the relationship between stage of growth and GDD deviates from the linear function at the early and late stages of growth, its accuracy is slightly reduced during this time period. Regression coefficients for the stage of growth method are given in Table 14. The equations of Kco as a function of stage of growth were developed as a practical method for on-farm use since stage of growth can be readily observed.

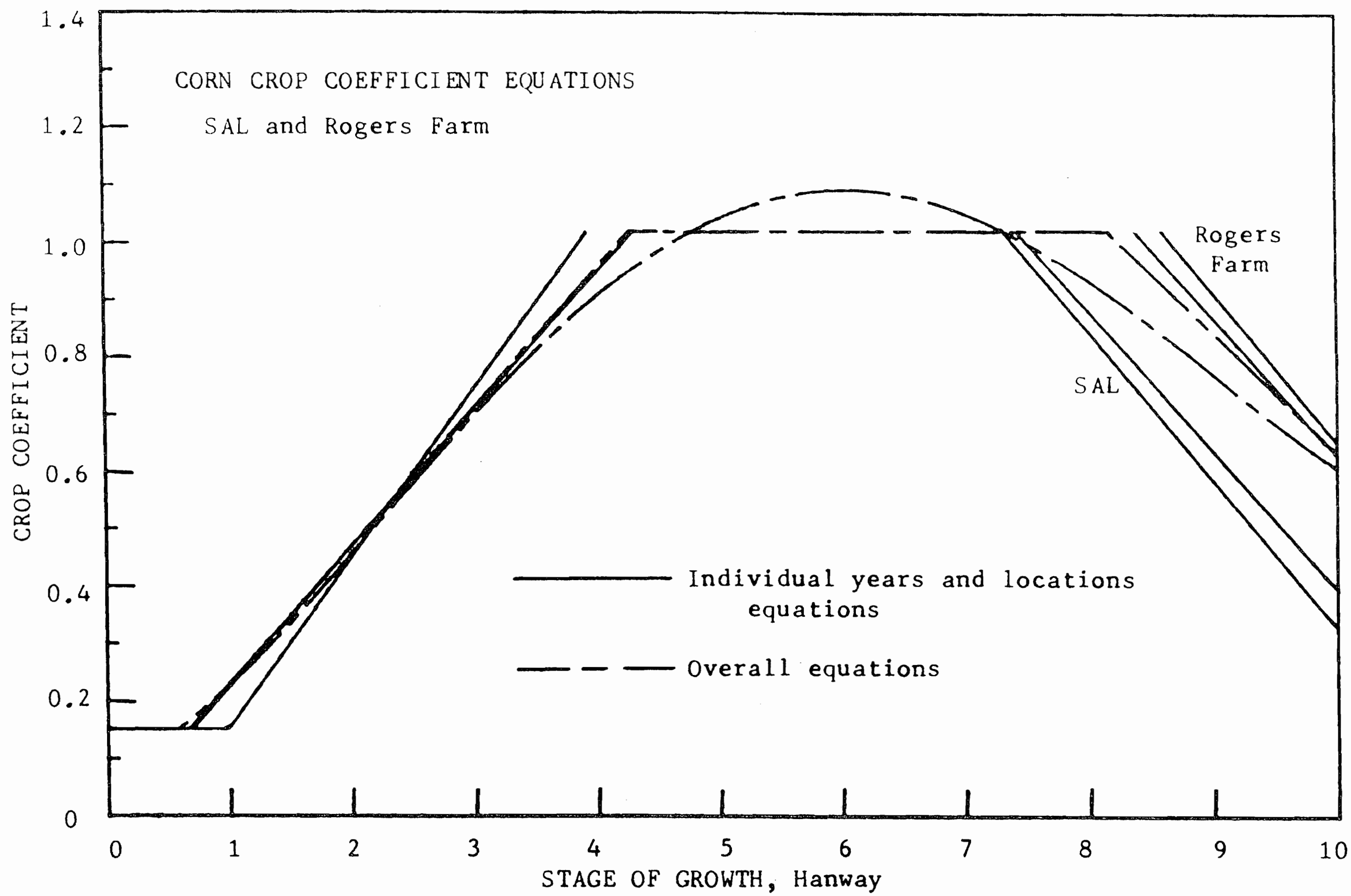

Figure 35. Overall corn crop coefficient equations as a function of stage of growth for the Rogers Farm and the Sandhills Ag. Lab.

Table 14. Regression coefficients for the crop coefficient corn for all sites and all years.[1]

Linear Model

Site	e	a	b	c	d	Corr. Coef.
Rogers Farm	0.15	-0.007	0.238	0.66	4.43	0.770
SAL	0.15	-0.139	0.295	0.99	3.83	0.756
ALL	0.15	-0.016	0.243	0.69	4.27	0.740

Site	f	g	h	p	q	Corr. Coef.
Rogers Farm	1.05	3.060	-0.243	8.29	10.0	0.587
SAL	0.99	2.920	-0.259	7.44	10.0	0.561
ALL	1.02	2.740	-0.211	8.17	10.0	0.500

Polynomial Model

Site	F	r	s	Corr. Coef.
Rogers Farm	0.15	0.6	10.0	0.779
SAL	0.15	0.6	10.0	0.572
ALL	0.15	0.6	10.0	0.689

Site	A	B	C	D	E
Rogers Farm	0.0605	0.1507	0.0409	-0.0079	0.00029
SAL	0.0340	0.0994	0.0936	-0.0192	0.00093
ALL	0.0805	0.0810	0.0806	-0.0150	0.00066

[1] Independent variable is stage of growth. Linear model is described by equations 4-7, polynomial model is described by equations 8-9.

GRAIN SORGHUM EXPERIMENTS

Grain sorghum (Sorghum bicolor) was grown at the Sandhills Ag. Lab. during 1978. The crop ET and potential ET was measured with lysimeters. In addition, Penman potential ET was calculated using weather data taken on site. Crop coefficient values were calculated as a ratio of sorghum ET to potential ET (Hejrati, 1980).

Grain sorghum variety RS626 was planted on May 23, emerged on June 3, 1978, and was mature on September 9. The plant population was approximately 173000 pl/ha (70000 pl/ac) with a row crop spacing of 76 cm (30 in). Both fertilization and weed control were adequate.

Evapotranspiration was measured using the lysimeters under three water treatments of full irrigation, limited irrigation (50% of ET), and no irrigation (dryland). The limited irrigation treatments began June 12. Using an estimate of 1.2 cm (0.5 in) for the amount of ET from plant emergence to June 12, seasonal amounts of ET (emergence to maturity) were 50.2, 41.7 and 31.0 cm (19.8, 16.4 and 12.2 in) for the three respective water treatments.

Growth parameters measured on the fully irrigated grain sorghum were leaf area and stage of growth. The stages of growth for grain sorghum are described by R.L. Venderlip (1972) and are tabulated in Table 15. Tabulation of leaf area index and stage of growth values along with cumulative 50-86 growing degree days are given in Table 16, and shown in Figures 36 and 37, respectively.

Potential ET was determined by two methods at the Sandhills Ag. Lab. during 1978. Method one used lysimeters which measured potential ET of a well watered alfalfa crop. Alfalfa was grown in two lysimeters in a field near the grain sorghum lysimeters. The lysimeters were alternately cut to provide a potential ET measurement throughout the growing season. Method two used a modified form of the Penman potential ET equation which was calibrated at a location with climatic conditions similar to those at the Sandhills Ag. Lab.

Table 15. Stages of growth for grain sorghum.[1]

Growth stage	Identifying characteristic
0	Emergence. Coleoptile visible at soil surface.
1	Collar of 3rd leaf visible.
2	Collar of 5th leaf visible.
3	Growing point differentiation. Approximately 8-leaf stage by previous criteria.
4	Final leaf visible in whorl.
5	Boot. Head extended into flag leaf sheath.
6	Half-bloom. Half of plants at some stage of bloom.
7	Soft dough.
8	Hard dough.
9	Physiological maturity. Maximum dry matter accumulation.

[1] From Vanderlip (1972).

Table 16. Leaf area index and stage of growth values for grain sorghum at SAL during 1978.

Date	Event	Cumulative 50-86 GDD from emergence	Leaf Area Index	Stage of Growth
May 23	planting	---	---	---
June 3	emergence	0	0	0
June 26		425	0.20	2.7
July 3		579	0.87	3.2
July 10		716	1.95	3.5
July 19		923	2.68	4.0
August 1		1179	2.78	5.2
August 17		1463	2.75	6.5
August 23		1577	2.55	7.2
September 9	maturity	1911	2.12	9.0

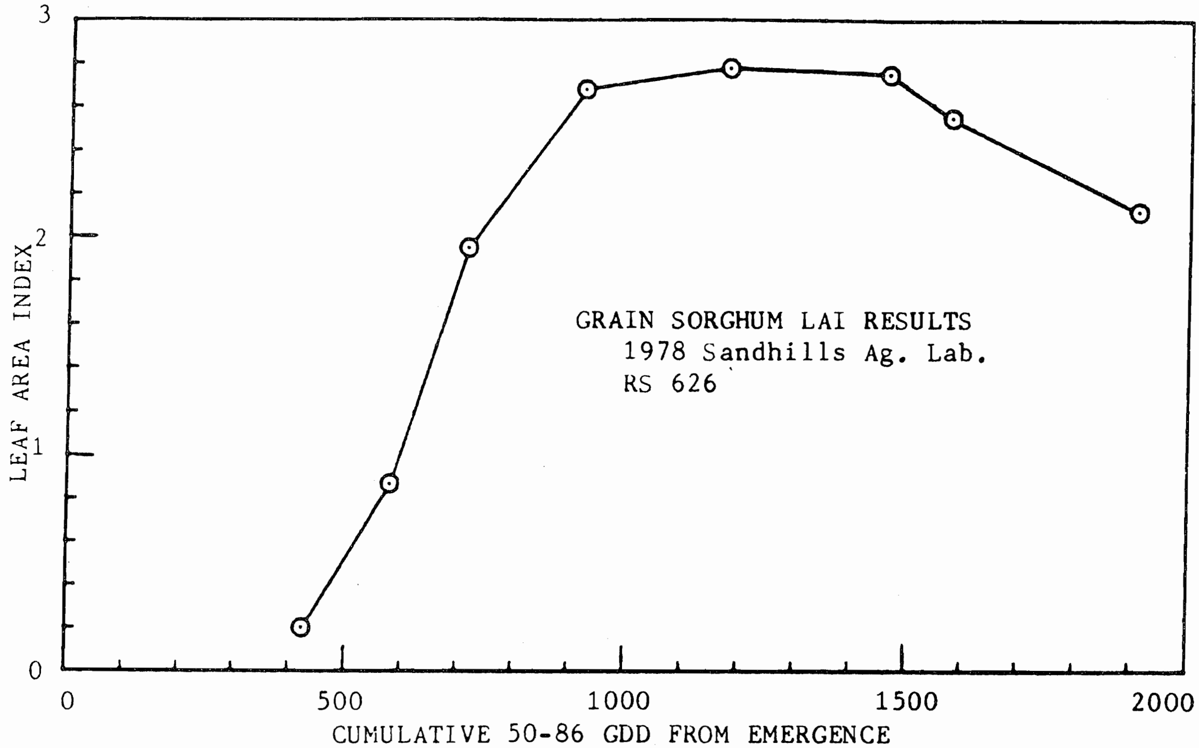

Figure 36. Grain sorghum leaf area index results for variety RS 626 at the Sandhills Ag. Lab. during 1978.

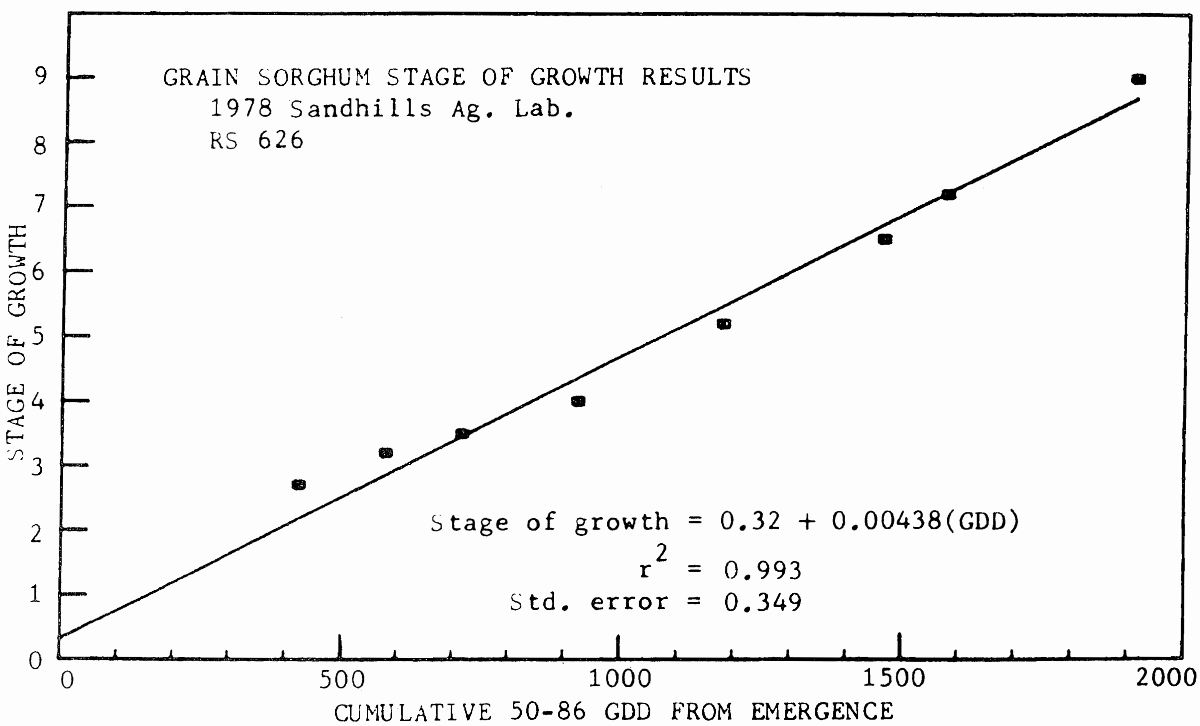

Figure 37. Grain sorghum stage of growth results for variety RS 626 at the Sandhills Ag. Lab. during 1978.

Potential ET measured with the alfalfa lysimeters was compared to potential ET calculated with the modified Penman equation (Figure 38). The alfalfa lysimeters estimated larger potential ET amounts during the middle portion of the growing season. Several reasons for the difference included lysimeter problems, inaccurate hygrothermograph measurements, and inaccurate potential ET calculations (Kranz, 1981). Since the error could not be traced to any one problem, the potential ET values by both methods were averaged to obtain a single estimate of potential ET.

Evapotranspiration values for the fully irrigated lysimeter and the average of the Penman and lysimeter measured potential ET were used to determine the crop coefficient values for grain sorghum. The resulting crop coefficients were found for five day periods throughout the measurement period. These values along with polynomial and linear equations for fraction of seasonal 50-86 GDD and stage of growth are shown in Figures 39 and 40, respectively. The coefficients for the linear and polynomial models are given in Table 17. The end of the Kco increasing period in Figure 39 was at the first data point with a Kco value greater than 1.0 and the beginning of the Kco decreasing period used a similar criteria.

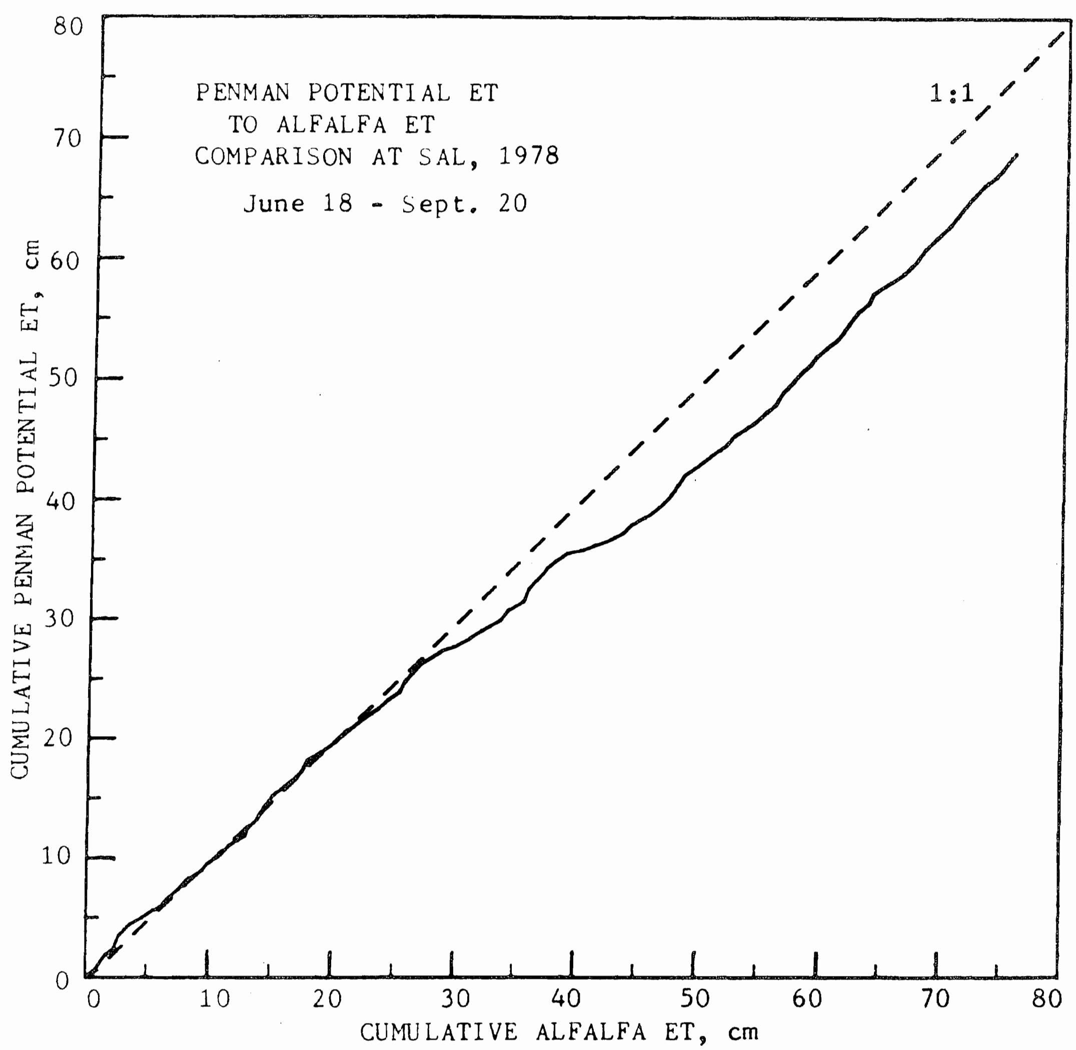

Figure 38. Comparison of Penman potential ET to lysimeter measured alfalfa ET at the Sandhills Ag. Lab. during 1978.

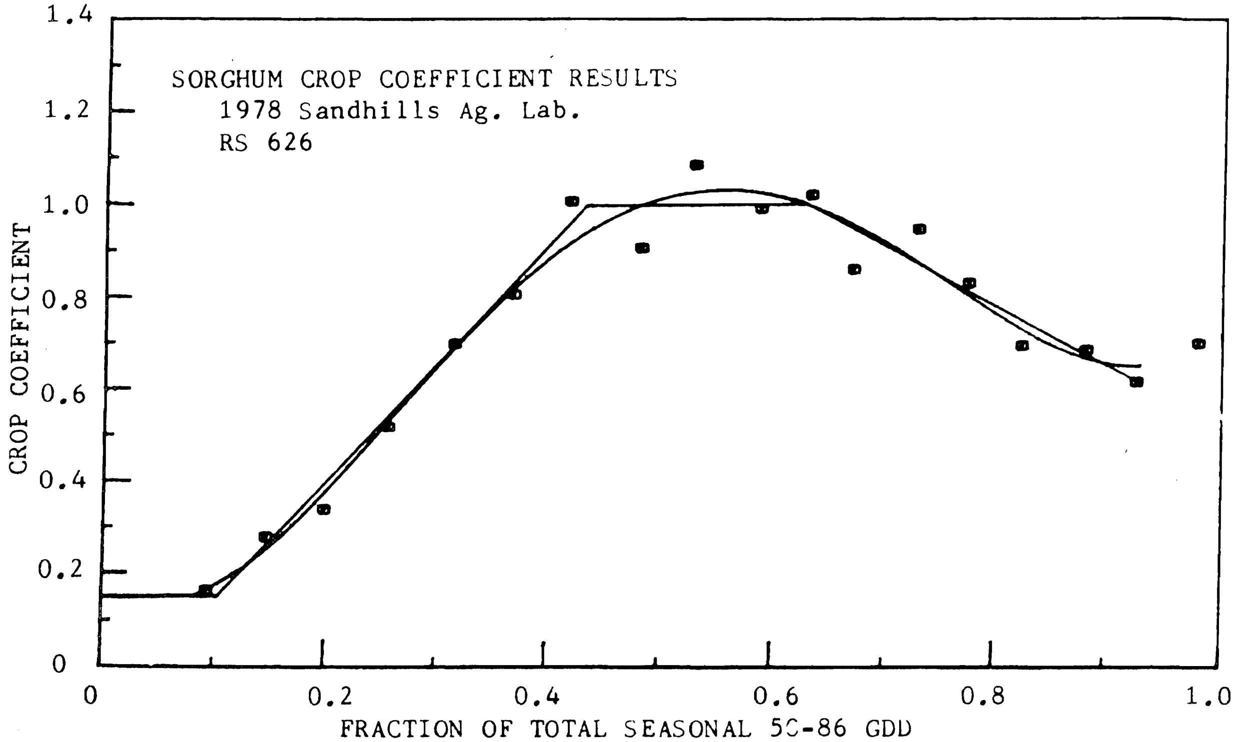

Figure 39. Grain sorghum crop coefficient results as a function of total seasonal 50-86 GDD at SAL during 1978.

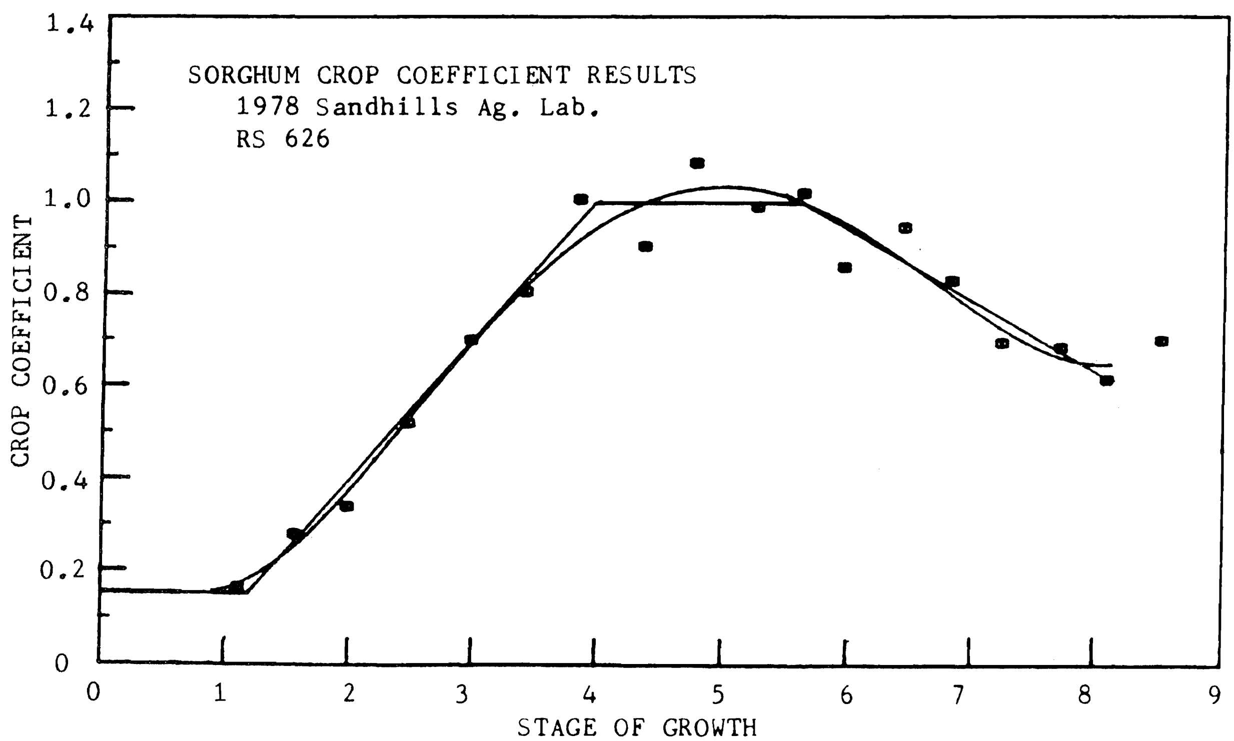

Figure 40. Grain sorghum crop coefficient results as a function of stage of growth at SAL during 1978.

Table 17. Regression coefficients for the crop coefficient for grain sorghum from SAL during 1978.[1]

Linear Model

Independent variable	e	a	b	c	d
GDD [2]	0.15	-0.113	2.555	0.10	0.44
SOG [3]	0.15	-0.208	0.304	1.20	4.00

Independent variable	f	g	h	p	q
GDD [2]	1.00	1.808	-1.286	0.63	0.93
SOG [3]	1.00	1.857	-0.154	5.60	8.10

Polynomial Model

Independent variable	F	r	s
GDD [2]	0.15	0.09	1.00
SOG [3]	0.15	1.00	8.10

Independent variable	A	B	C	D	E
GDD [2]	0.1431	-1.178	17.421	-30.708	14.992
SOG [3]	0.2285	-0.331	0.306	-0.0570	0.00309

[1] Linear model is described by equations 4-7, polynomial model is described by equations 8-9.

[2] Fraction of seasonal 50-86 GDD.

[3] Stage of growth.

SOYBEAN EXPERIMENTS

Soybeans were grown in the lysimeters at the Rogers Farm during 1982 (Nolette, 1983). Three replications of two soybean varieties were inoculated with Rhizobium japonicum bacteria to induce nodule formation and were planted on June 12. Hobbit soybeans were planted in 25.4 cm (10 in) row spacing with a plant population of 527,000 plants/hectare (312,400 plants/acre). This variety has a determinate growth habit and belongs to maturity group III. Williams soybeans were planted in 76.2 cm (30 in) rows with a plant population of 351,000 plants/hectare (142,100 plants/acre). This variety has an indeterminate growth habit and belongs to the maturity group III. Plant emergence occurred on June 21 for both varieties. The Hobbit variety matured in 109 days on October 8 and the Williams variety matured in 114 days on October 13. Irrigation water was applied as needed based upon soil moisture conditions measured with a neutron probe. Because of frequent rainfall events only three irrigation events took place in 1982.

Potential evapotranspiration was calculated using the modified Penman equation as presented by Kincaid and Heermann (1974). Weather data used in the calculations was collected at a standard weather station near the lysimeters.

The stage of plant growth was measured every three to seven days throughout the growing season using the scale developed by Ritchie et al. (1982) which is given in Table 18. The stages of growth for both varieties and the cumulative growing degree days (GDD) are given in Table 19. The growing degree days were calculated using mean daily temperature with a base temperature of 10°C (50°F) and a peak maximum temperature of 50°C (86°F). The resulting relationships between stage of growth and GDD are given in Figures 41 and 42.

Table 18. Stages of growth for soybeans. [1]

Vegetative Stages		Reproductive Stages	
VE	Emergence	R1	Beginning bloom
VC	Cotyledon	R2	Full bloom
V1	First-node	R3	Beginning pod
V2	Second-node	R4	Full pod
V3	Third-node	R5	Beginning seed
		R6	Full seed
		R7	Beginning maturity
V(n)	nth-node	R8	Full maturity

[1] From Ritchie et al. (1982).

Table 19. Soybean stage of growth in 1982. [1]

Date	Cumulative 50-86 GDD from emergence	Williams Stage of Growth	Hobbit Stage of Growth
June 21	0	V0.0	V0.0
June 24	67	V0.5	V0.5
June 28	159	V1.5	V1.5
July 1	229	V2.0	V2.0
July 6	369	V3.0	V3.4
July 9	444	V3.8	V4.3
July 16	624	V5.7	V6.5
July 23	818	V7.8	V8.1
July 27	921	R1.8	R2.0
July 30	983	R2.2	R2.2
August 2	1062	R2.4	R2.5
August 9	1245	R3.0	R3.8
August 13	1303	R3.6	R4.8
August 19	1438	R4.7	R5.4
August 23	1525	R5.1	R5.9
August 27	1589	R5.5	R6.0
September 1	1694	R5.8	R6.2
September 8	1837	R6.0	R6.4
September 15	1952	R6.2	R6.6
September 22	2004	R6.4	R6.8
October 1	2121	R6.8	R7.3
October 4	2161	R7.0	R7.7
October 8	2212	R7.5	R8.0
October 13	2226	R8.0	--

[1] Using the stage of growth definitions from Ritchie et al. (1982) given in Table 18.

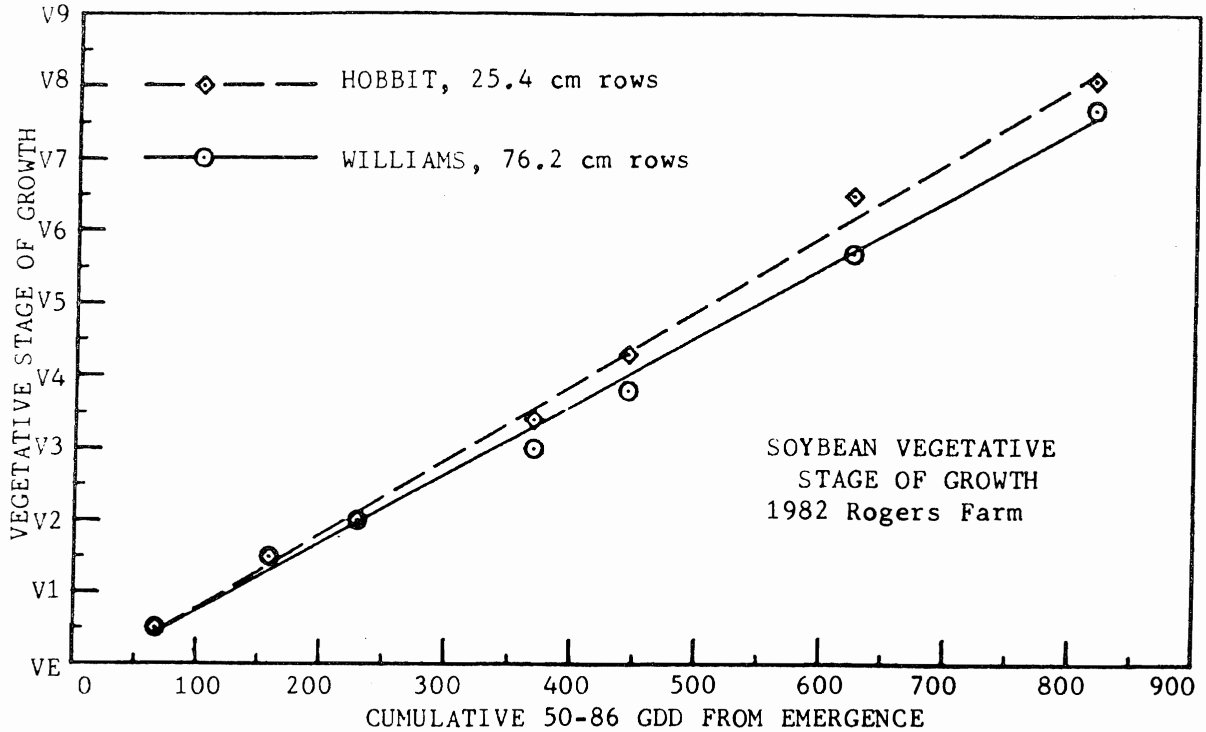

Figure 41. Soybean vegetative stage of growth results from the Rogers Farm during 1982.

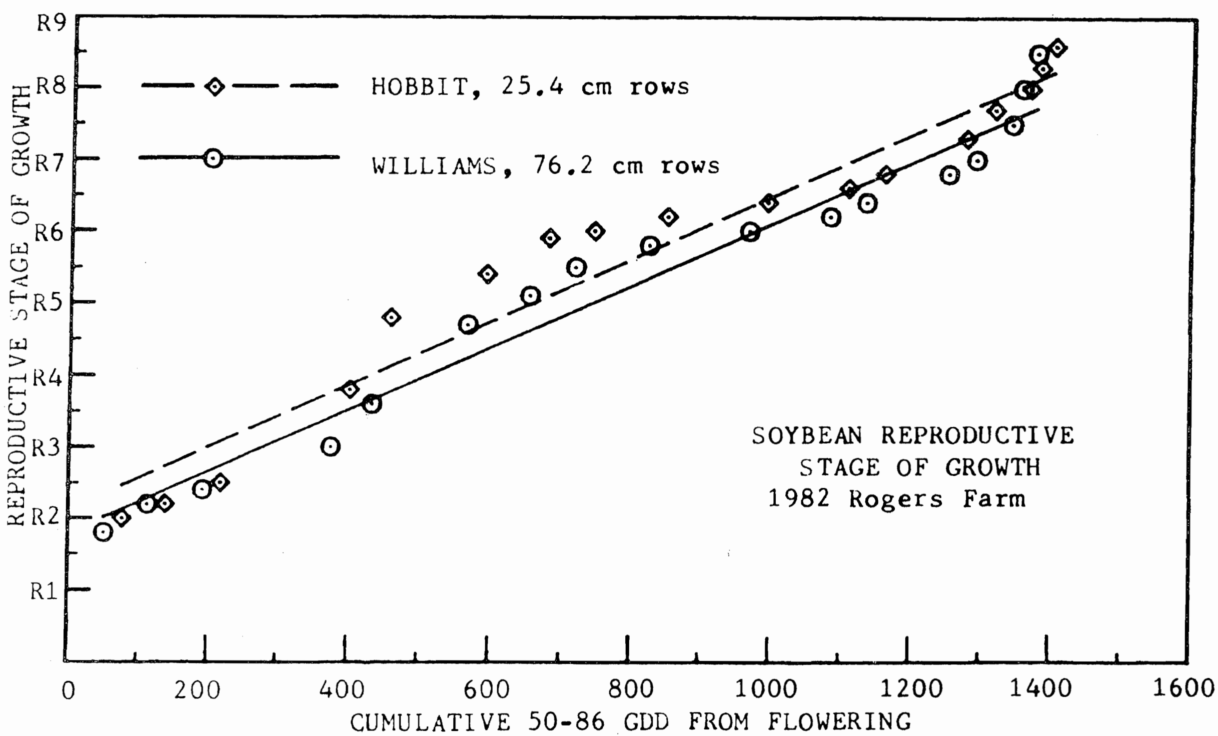

Figure 42. Soybean reproductive stage of growth results from the Rogers Farm during 1982.

The daily crop ET was determined and accumulated for each of the three lysimeters for each variety. The average of cumulative ET for both varieties is shown in Figure 43. The seasonal ET for the Hobbit variety was 62.1 cm (24.4 in) and the seasonal ET for the Williams variety was 64.2 cm (25.3 in).

The ET from each lysimeter was corrected for soil evaporation after a rain or an irrigation event to obtain the basal ET values. Daily crop coefficients for both varieties were obtained by averaging the three daily values from the irrigated lysimeters for each variety. Two day averages were then used to calculated the crop coefficient. The resulting crop coefficients for Hobbit and Williams varieties as a function of fraction of seasonal GDD are given in Figures 44 and 45, respectively. Crop coefficients for both varieties as a function of stage of growth are shown in Figures 46 and 47. The regression coefficients for the linear model for the soybean crop coefficients are summarized in Table 20.

The peak-period crop coefficients for both varieties (1.27 for the Williams variety and 1.15 for the Hobbit variety) are relatively large. There are two possible reasons for these high values. First, the 1982 growing season was abnormally wet with frequent rainfall events. Only three irrigations were required late in the growing season. Because of the frequent rainfall and the resulting wet soil surface, the extra soil surface evaporation taking place under these conditions may have been underestimated using the methodology described earlier, and the resulting crop coefficients are not the true basal values. Secondly, the reference or potential ET for the relatively wet and cool climatic conditions experienced in 1982 may have been underestimated using the Penman equation which was calibrated for western Nebraska. Corrections to the crop coefficients for these two possible errors were not attempted, thus the crop coefficients given here are probably high.

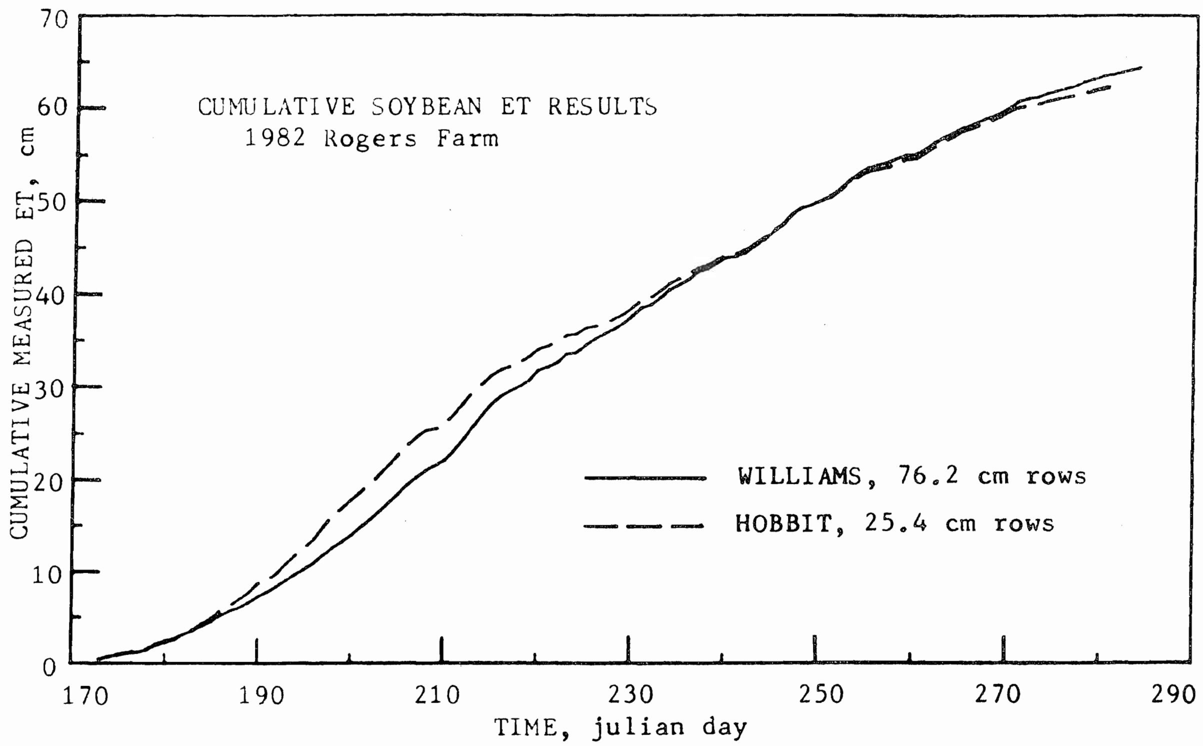

Figure 43. Cumulative soybean ET of Williams and Hobbit varieties at the Rogers Farm during 1982.

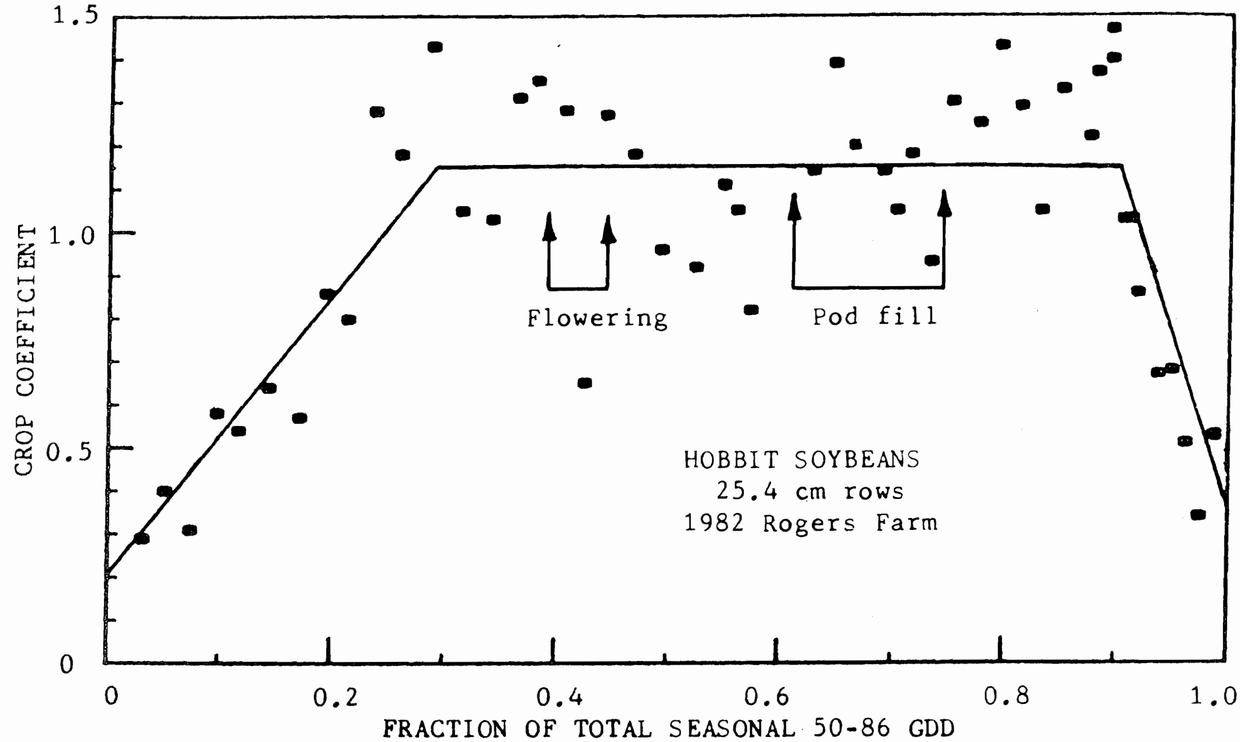

Figure 44. Crop coefficient results for Hobbit soybeans in 25.4 cm rows at the Rogers Farm during 1982.

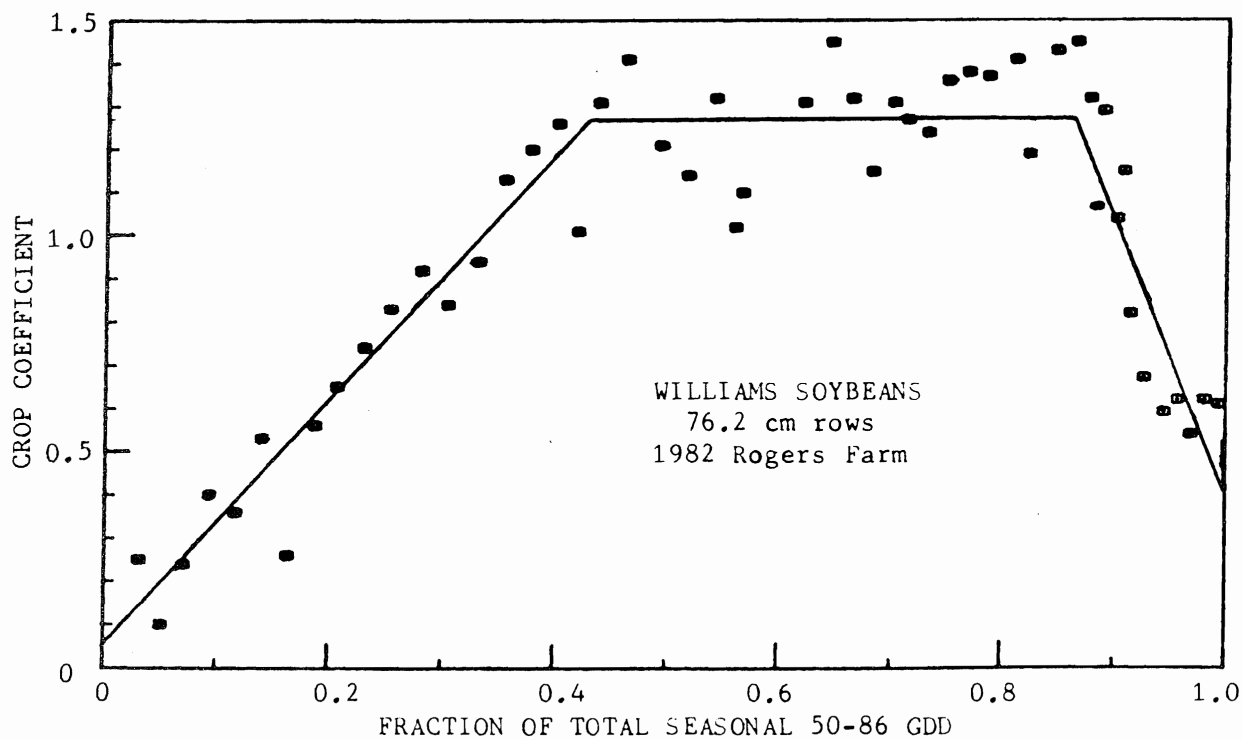

Figure 45. Crop coefficient results for Williams soybeans in 76.2 cm rows at the Rogers Farm during 1982.

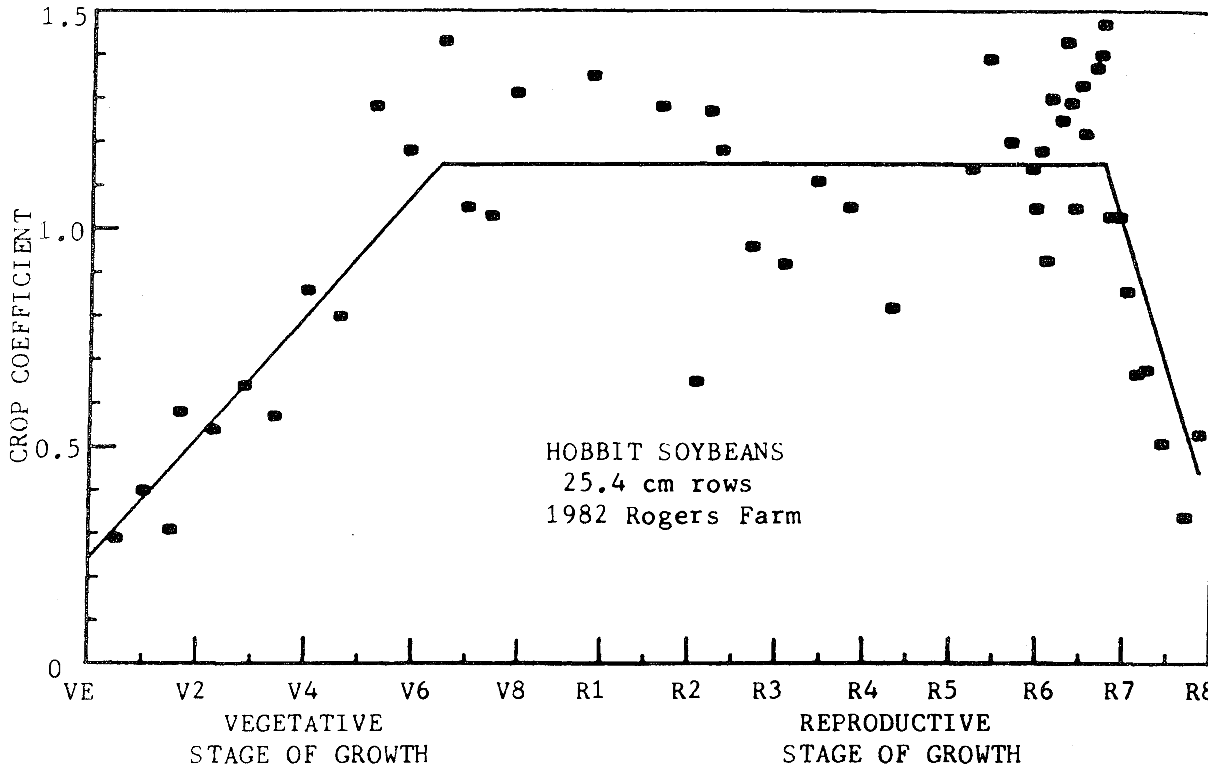

Figure 46. Crop coefficient results for the Hobbit soybeans as a function of stage of growth at the Rogers Farm during 1982.

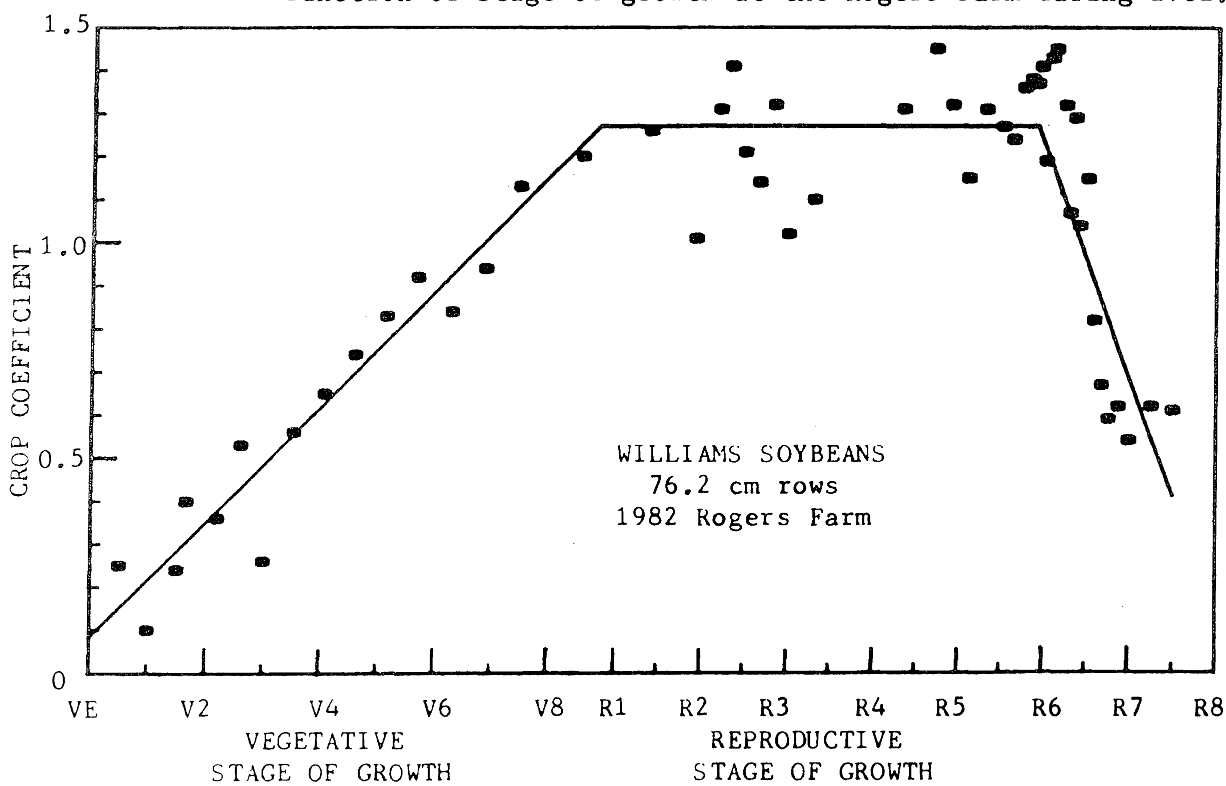

Figure 47. Crop coefficient results for the Williams soybeans as a function of stage of growth at the Rogers Farm during 1982.

Table 20. Regression coefficients for the soybean crop coefficient from the Rogers Farm in 1982.[1]

Linear Model

Variety	Independent Variable	e	a	b	c	d
Hobbit	GDD [2]	0	0.20	3.276	0	0.29
Hobbit	SOG [3]	0	0.25	0.138	VE	V6.5
Williams	GDD [2]	0	0.05	2.837	0	0.43
Williams	SOG [3]	0	0.10	0.138	VE	V8.5 (R0.5)

Variety	Independent Variable	f	g	h	p	q
Hobbit	GDD [2]	1.15	7.900	-7.500	0.90	1.0
Hobbit	SOG [3]	1.15	5.015	-0.577	R6.7	R8.0
Williams	GDD [2]	1.27	6.614	-6.214	0.86	1.0
Williams	SOG [3]	1.27	4.750	-0.580	R6.0	R7.5

[1] Linear model is described by equations 4-7.

[2] Fraction of seasonal 50-86 GDD.

[3] Stage of growth.

SUMMARY

New crop coefficients were developed for use in calculation of crop evapotranspiration for a particular crop at a given growth stage given the potential evapotranspiration. The coefficients are basal or minimal coefficients, representing conditions when the soil evaporation is minimal but root-zone soil moisture is adequate. Basal crop coefficients were developed for corn, grain sorghum and soybeans using fraction of seasonal growing degree days and stage of growth. They can be used with current irrigation scheduling programs for estimating daily crop ET and should increase the accuracy of the irrigation scheduling procedures and estimates of crop water requirements, especially when crop development is modified by changes from normal weather conditions. The growth stage basis of expressing the crop coefficients should also be useful in developing irrigation management guidelines as the stage of growth can be readily observed.

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APPENDIX A

Crop Coefficients for Each Corn Variety at the Rogers Farm in 1981

Table A1. Linear regression coefficients for the corn crop coefficients at the Rogers Farm in 1981. [1]

Variety	e	a	b	c	d	Corr. Coef.
VAR80	0.15	-0.295	2.919	0.15	0.45	0.69
VAR85	0.15	-0.343	3.099	0.16	0.46	0.89
VAR100	0.15	-0.190	2.741	0.12	0.44	0.79
VAR105	0.15	-0.286	3.024	0.14	0.45	0.84
VAR120	0.15	-0.320	3.706	0.13	0.38	0.90
VAR140	0.15	-0.322	3.208	0.15	0.45	0.80
ALL except VAR120	0.15	-0.290	3.014	0.15	0.45	0.81

Variety	f	g	h	p	q	Corr. Coef.
VAR80	1.01	4.121	-3.796	0.82	1.0	0.84
VAR85	1.08	3.720	-3.141	0.84	1.0	0.68
VAR100	1.02	3.301	-2.876	0.79	1.0	0.89
VAR105	1.07	4.010	-3.628	0.81	1.0	0.73
VAR120	1.08	3.377	-2.815	0.82	1.0	0.46
VAR140	1.13	3.391	-2.869	0.79	1.0	0.45
ALL	1.07	3.570	-3.094	0.81	1.0	0.58

[1] Independent variable is fraction of seasonal 50-90 stress GDD. Linear model is described by equations 4-7.

Table A2. Polynomial regression coefficients for corn crop coefficients at the Rogers Farm in 1981.[1]

Variety	F	r	s	Corr. Coef.
VAR80	0.15	0.14	1.00	0.87
VAR85	0.15	0.14	1.00	0.88
VAR100	0.15	0.00	1.00	0.73
VAR105	0.15	0.12	1.00	0.80
VAR120	0.15	0.12	1.00	0.77
VAR140	0.15	0.13	1.00	0.75
ALL	0.15	0.12	1.00	0.77

Variety	A	B	C	D	E
VAR80	0.289	-3.138	20.380	-27.690	10.529
VAR85	-0.082	0.655	9.297	-15.630	6.480
VAR100	0.273	-1.761	17.430	-27.760	12.320
VAR105	-0.027	0.512	9.302	-14.460	5.045
VAR120	-0.522	6.666	-9.162	5.779	-2.185
VAR140	-0.126	1.299	7.152	-11.930	4.097
ALL	0.026	-0.043	11.195	-17.422	6.716

[1] Independent variable is fraction of seasonal 50-90 stress GDD. Polynomial model is described by equations 8-9.

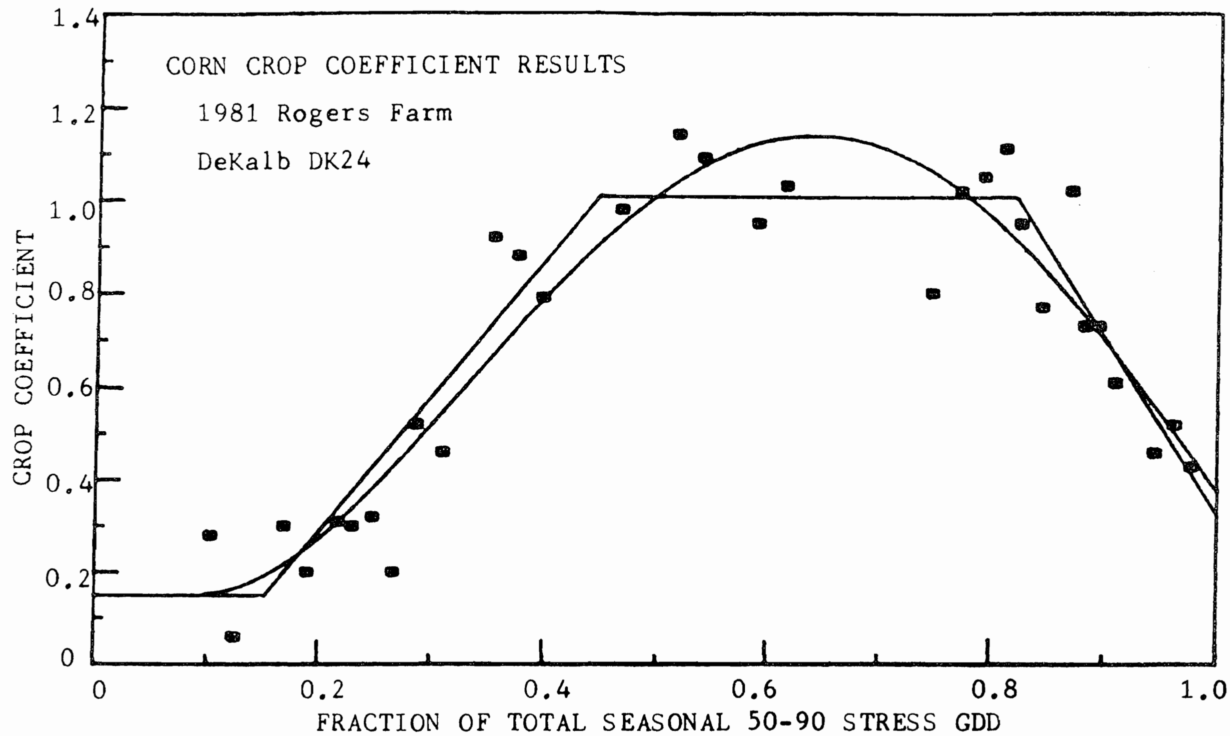

Figure A1. Corn crop coefficient results for a 80 day maturity variety at the Rogers Farm during 1981.

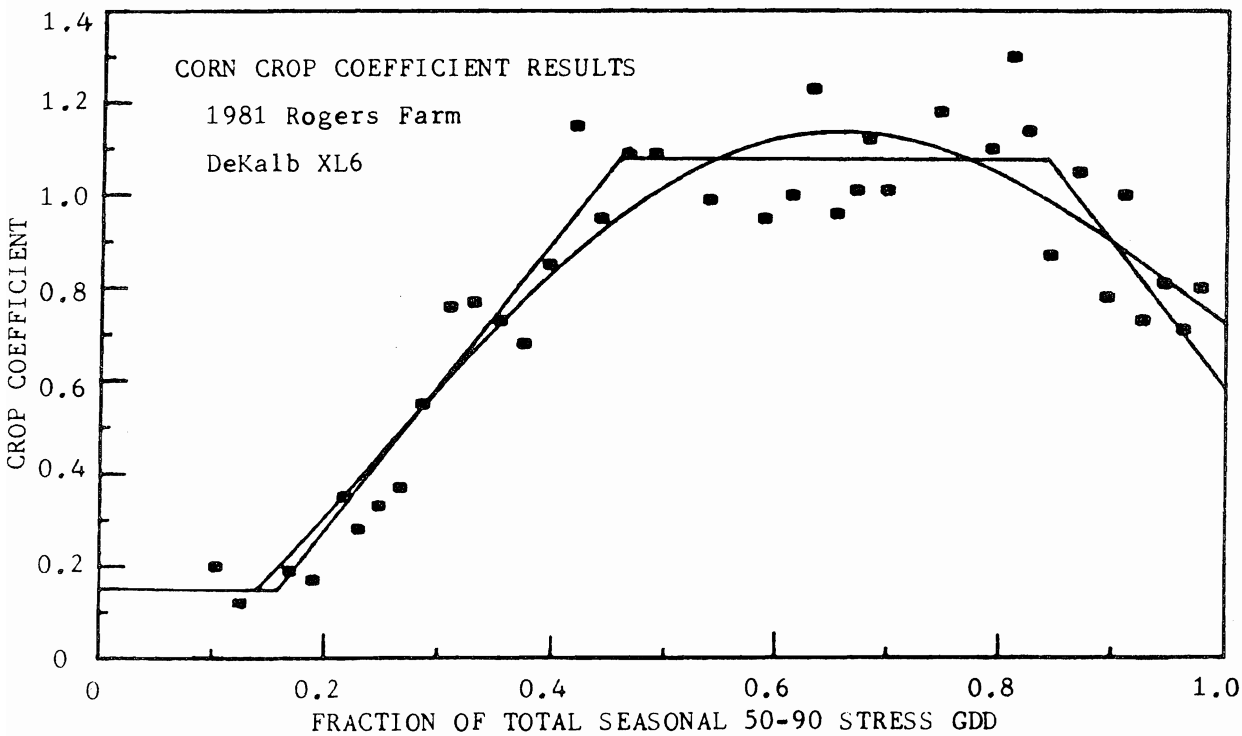

Figure A2. Corn crop coefficient results for a 85 day maturity variety at the Rogers Farm during 1981.

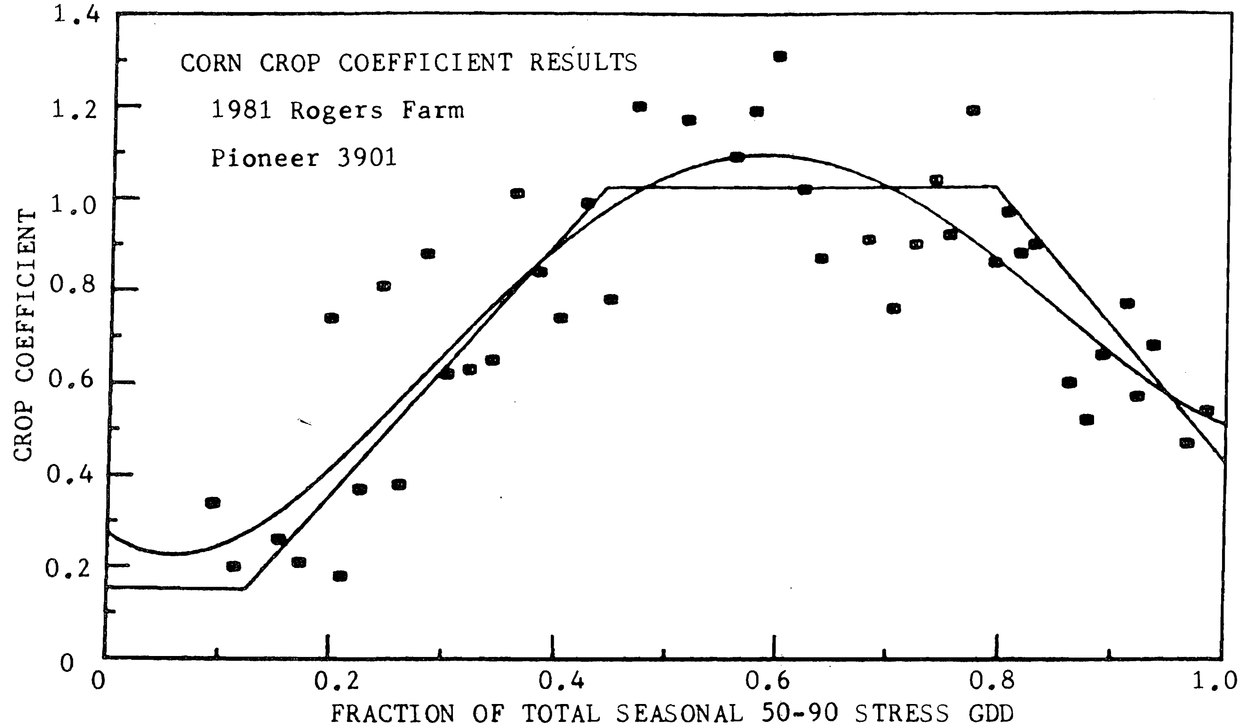

Figure A3. Corn crop coefficient results for a 100 day maturity variety at the Rogers Farm during 1981.

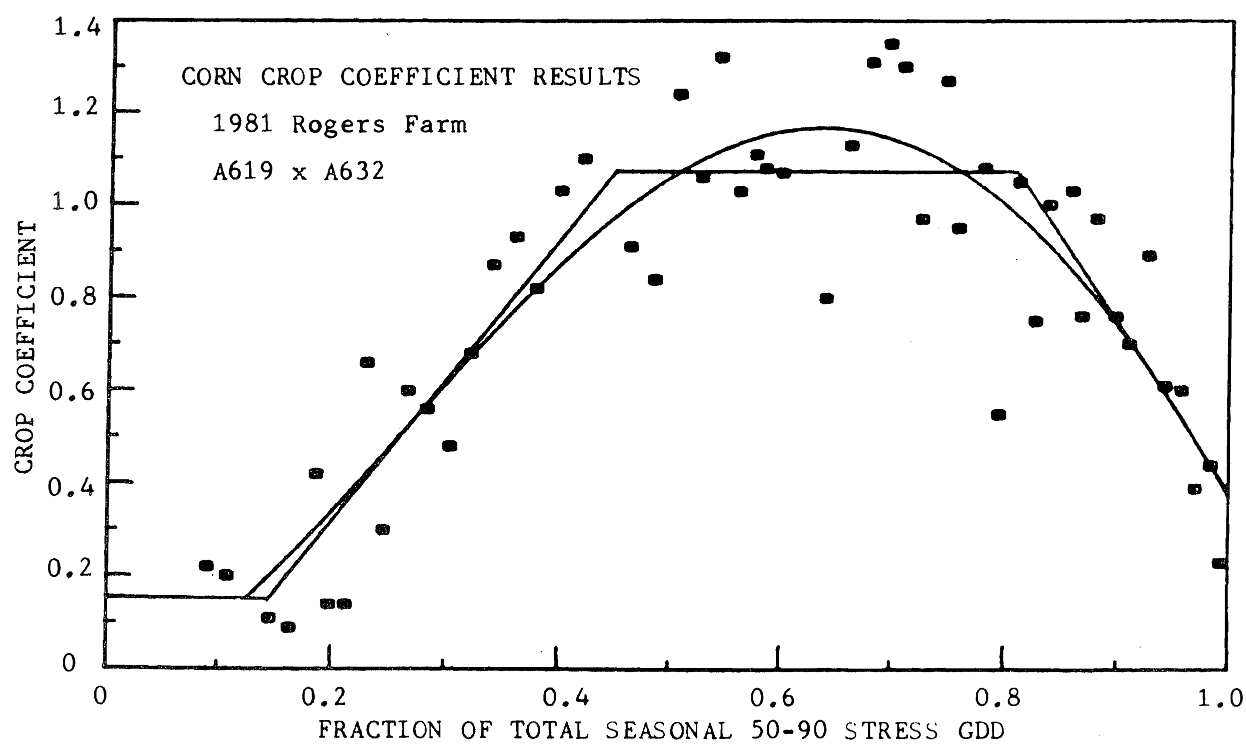

Figure A4. Corn crop coefficient results for a 105 day maturity variety at the Rogers Farm during 1981.

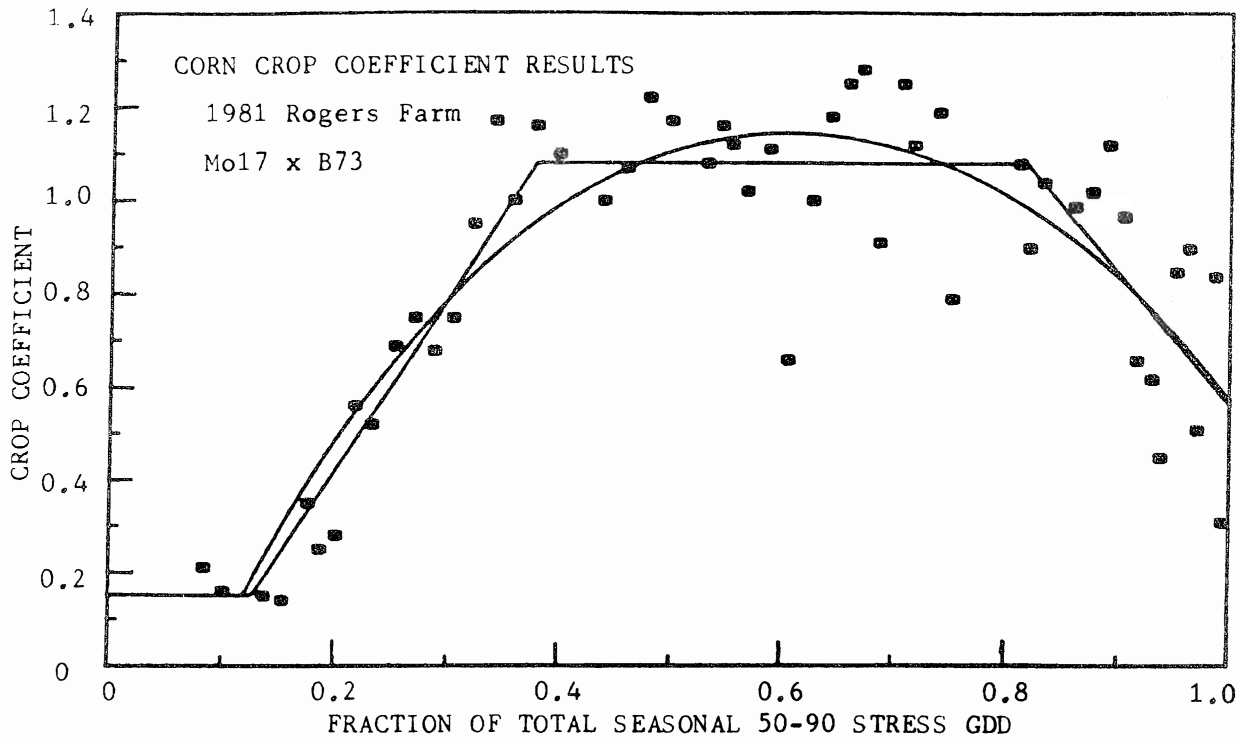

Figure A5. Corn crop coefficient results for a 120 day maturity variety at the Rogers Farm during 1981.

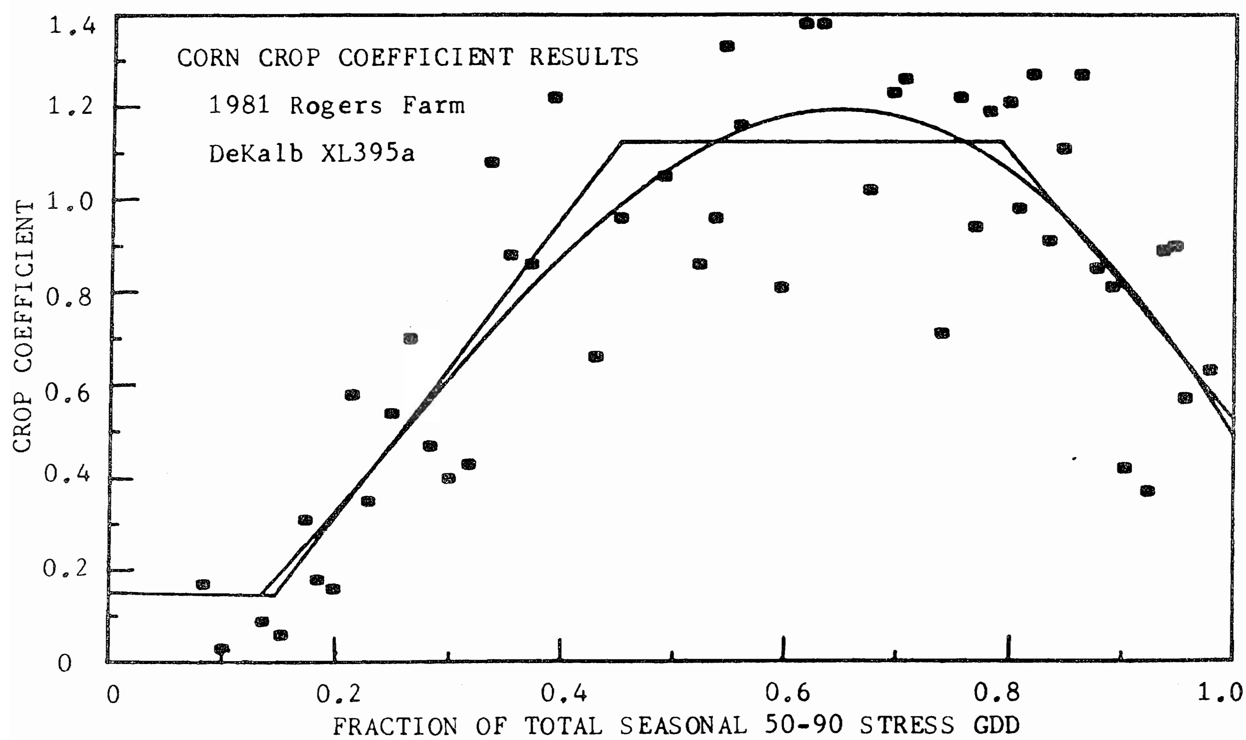

Figure A6. Corn crop coefficient results for a 140 day maturity variety at the Rogers Farm during 1981.