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THE AGROCLIMATOLOGY OF A MOISTURE STRESS INDEX AND AVERAGE CORN (*ZEA MAYS* L.) YIELDS IN TIPPECANOE COUNTY, INDIANA, 1961-1991

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ABSTRACT: Weather is the most important uncontrolled variable in crop production. Yet, its effect on crop yield is difficult to quantify in field environments where agricultural technology continually acts to increase yield potential. A single moisture stress index and a technology trend variable were used to estimate the weather effects on average county corn (*Zea mays L.*) yields, and then the climatology of that index for Tippecanoe County, Indiana, was prepared based on the 1961-1991 record. The ratios of actual evapotranspiration to potential evapotranspiration (ET/PET) were computed on a daily basis and summed to obtain moisture stress indices for three periods — 120, 90, and 37 days — of corn growth and development, each bracketing the date of corn silking. Two models, a 37-day stress index with a linear technology or trend variable and a 90-day stress index with the same technology variable plus a weather-technology interaction term, had adjusted R-squares of 0.68 and root MSEs of 0.81 t ha^{-1}. In the 1961-1991 period, the 37-day stress was most severe in 1991, but the full-season (120-day) and 90-day stresses were most severe in 1988. Climatological frequencies of the moisture stress indices for each of the three critical periods were highly negatively skewed, indicating a much greater probability for "favorable corn weather" than for severe moisture stress in Tippecanoe County. The climatological probability of having a 37-day stress index of 34 or greater (little or no stress) is 50%. With 1992 technology and a 37-day stress index of 34, the average corn yield for Tippecanoe County is predicted at 9.3 t ha^{-1} (149 bu a^{-1}).

INTRODUCTION

Weather is the most important uncontrolled variable in crop production, but its effect on crop yields is difficult to quantify in field environments where agricultural technology continually acts to increase yield potential. Efforts to evaluate the weather effects on crop development, growth, and final yield have ranged from complex biophysical simulation models to multiple regression models using many variables (Acock and Acock, 1991). The principal weather variables affecting crop growth and final yield are solar radiation, temperature, and soil moisture. All three of these variables are important, but in the U.S. Corn Belt, soil moisture is the most variable and therefore most often the major limiting factor in determining crop yields. While agricultural technology has continued to increase corn (*Zea mays* L.) yield potential, the actual yields in Indiana are still occasionally severely reduced by moisture stress, as observed in Tippecanoe County in 1983, 1988, and 1991. To quantify the weather effects on corn growth and final yields and to simplify the climatological description of "favorable corn weather", a single soil moisture stress index was used in which the daily soil water supply and the atmospheric evaporative demand on the corn crop were considered. The soil moisture stress index was defined as the sum of the daily ratios of the computed actual corn evapotranspiration to the potential evapotranspiration (ET/PET) over a given phenological period.

Whether one calculates a moisture stress variable or uses just rainfall and temperature data to correlate with corn yields, the timing of the moisture stress or rainfall with regard to corn development — corn phenology — is important in assessing weather effects on final grain yields. Even in studies in which corn yields were correlated with weather variables summed over non-phenological periods, e.g., monthly total rainfall and mean temperatures, the weather during July, in which corn silking usually occurs, has proven to be the most important predictor of State average corn yields in the U.S. Corn Belt (Thompson, 1969). Shaw (1977) summarized the experimental work of several researchers to show that moisture stress during the late vegetative stage of corn through silking had the greatest effect on final yields. However, Dale (1948), using Story County, Iowa, average corn yields, and Changnon and Neill (1968), using corn yields from 60 farms in central Illinois, found that 3-week rainfall totals centered 4 to 6 weeks before silking and again 2 weeks after silking were more highly correlated with final corn yields than was rainfall during the time of corn tasseling and silking. Agronomically, corn growth curves show rapid, almost linear, dry weight increases from 4 weeks before silking to 6 weeks after (Hanway and Russell, 1969). Stuff, *et al.* (1979, Figures 13 and 14) found that vegetative corn growth rates peaked 2 weeks before and 2 weeks after silking and that grain growth rates peaked two weeks after silking. In these periods, corn plant or grain dry weight increased an average of more than 300 kg ha^{-1} day^{-1}. Since the ear is being differentiated about 4-6 weeks before silking (Sass and Loeffel, 1959), it is reasonable to expect that moisture stress occurring any time in the period from 6 weeks before to 6 weeks after silking can reduce corn yields. Dale and Hodges (1975) found that a daily energy-moisture stress variable, summed over the period from 6 weeks before silking to 6 weeks after silking, and the amount of nitrogen (N) applied to corn were associated with 76 percent of the variance in the Tippecanoe County average corn yields, 1954-1974.

In correlating corn yield with an unweighted sum of a daily moisture stress variable over any crop calendar period, the stress on any day in the summation period was assumed to have an equal effect on final grain yield. For estimating the economic feasibility of irrigating corn in Indiana, Paisarnuchapong (1981) correlated ($R = 0.74$) county corn yields with a moisture stress index summed over the entire corn growing season of 120 days. This period extended from planting (averaging 69 days before silking) to grain maturity about 50 days after silking. Mach and Dale (1983) correlated experimental plot corn yields with fertilizer nitrogen (N) and an energy-crop growth (ECG) variable summed over various phenological periods. The ECG is a product of the daily ET/PET ratio, the solar radiation intercepted by the corn leaf area (SR*FLAI), and a temperature function. They found the summation of ECG over a 90-day period, 39 days before to 50 days after silking, provided higher correlation with experimental plot corn yields than did ECG summations over other periods examined. Featherstone, *et al.* (1991) also used a 90-day summation of a moisture stress variable (1-ET/PET) to account for the weather influence in an economic study of corn yields from alternative tillage systems on 78 farm sites in Wabash County in 1983. Andresen, *et al.* (1989) found that ET/PET was the most important factor in ECG. In an optimization program, they found that the summation of a daily optimized ECG $((ET/PET)^2(SR*FLAI)^{0.25})$ over a 37-day period (16 days before to 20 days after silking) provided higher correlations with county average corn yields than other periods examined. The model was developed with data from

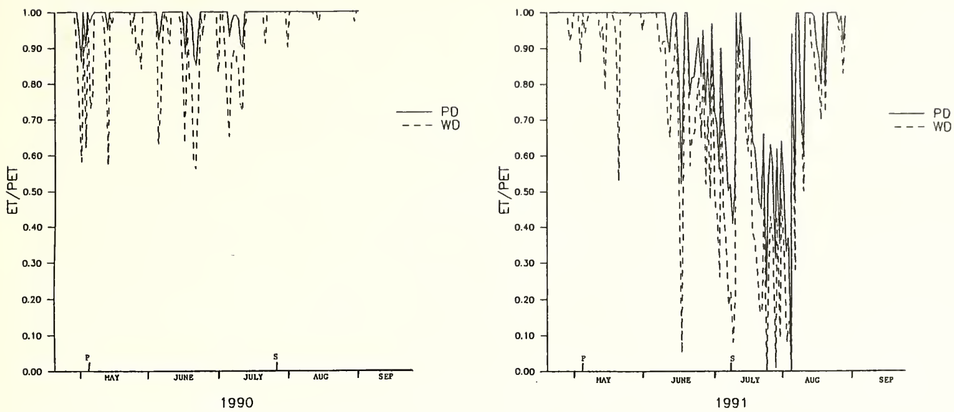

Figure 1. Daily series of ET/PET for poorly-drained and well-drained soils in Tippecanoe County for 1990 and 1991. The dates by which 50% of the District 4 corn acreage had been planted (P) and silked (S) are shown on the abscissa.

4 counties and independently tested with data from 14 other counties in Indiana (R = 0.83).

We have two objectives in this paper. The first is to show the relation of a technology trend and a soil moisture stress index summed over three periods, 120, 90, and 37 days, to the average corn yield in Tippecanoe County, Indiana. The second is to prepare the climatology of that moisture stress index based on the 1961-1991 period. Assuming that this climatological record is representative of the weather to come, the results of these two analyses will allow the probability of moisture stress and thereby the average corn yield for Tippecanoe County for 1992 and subsequent years to be estimated.

MATERIALS AND METHODS

The SIMBAL (simulation of the soil water balance) program developed by Stuff and Dale (1978) for corn on a tile-drained Typic Argiaquoll (Chalmers silt loam) and later generalized (Dale, *et al.,* 1982) for both poorly-drained (PD) and well-drained (WD) soils was used to calculate the soil moisture under corn and the ratio of actual to potential evapotranspiration (ET/PET) for each day of the growing seasons, 1961 through 1991, for representative PD and WD soils in Tippecanoe County. For PD soils, the soil water balance is controlled by the corn rooting depth (estimated from date of corn silking), the plant available water holding capacity in each soil layer, infiltrated precipitation, depth of the field drainage tiles, capillary flow upward from the shallow water table into the corn root zone, and the evapotranspiration loss. For WD soils, the simulation is the same except there is no modeled shallow water table and capillary flow into the corn root zone.

The daily precipitation and pan evaporation data were observed at the NWS-Purdue University climatological station, West Lafayette 6 NW, at the Agronomy Research Cen-

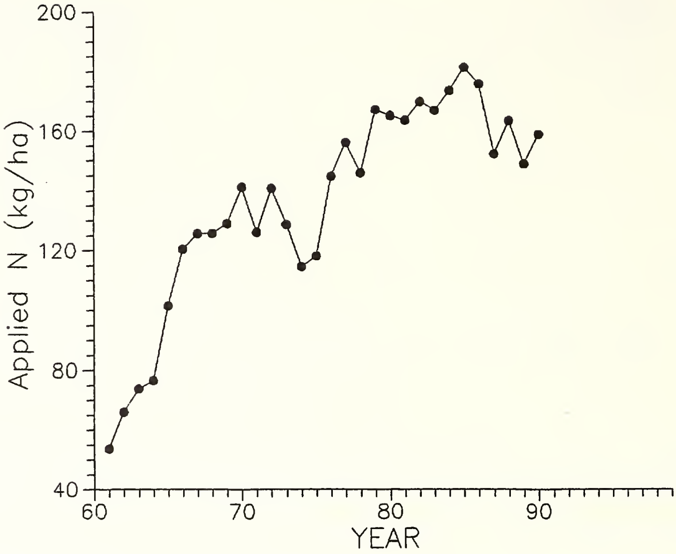

Figure 2. Indiana State average nitrogen applicawwwtion on corn land for indicated year, 1961-1990 (data from Indiana Agricultural Statistics Service).

ter (U.S. Dep. Commerce, 1961-1991). The soil characteristics for a representative PD soil in Tippecanoe County, a Typic Argiaquoll (Chalmers silt loam), were those used by Dale, *et al.* (1982, Table 1). This PD soil has a plant-available water holding capacity of 235 mm in the top 105 cm and an additional average capillary supply of about 87 mm from the shallow water table during the 100-day seasons centered at the date of corn silking (Stuff and Dale, 1978, Table 1). The soil characteristics for a representative WD soil, a Typic Argiudoll (Elston), were those used by Paisarnuchapong (1981, Table 3). This WD soil has a plant-available water holding capacity of 189 mm in the top 150 cm. The average date by which 50% of the corn acreage in Tippecanoe County had silked for each year was assumed to be the same as that for Crop Reporting District 4, published by the Indiana Agricultural Statistics Service (1961-1991).

In SIMBAL, the daily ET/PET ratio is calculated as a function of the product of the pan evaporation (E_p) and the soil moisture deficit (1-PAV), where PAV is the ratio of the plant-available soil water to the available water holding capacity in the corn root zone. If there is little E_p and little (1-PAV), the ET/PET ratio is 1, and there is no moisture stress. If E_p and/or (1-PAV) are great, ET/PET is less than 1, and the corn is stressed. While the ET/PET ratio is referred to as a measure of soil-plant "moisture stress", please note it is really a "non-moisture stress" variable, i.e., the higher the ET/PET the less the stress.

Plots of the calculated daily ET/PET ratios are shown in Figure 1 for both a PD (Chalmers, Typic Argiaquoll) and a WD (Elston, Typic Argiudoll) soil for 1990 and 1991. The differences shown in the seasonal ET/PET patterns raised two procedural questions which had to be answered.

First, moisture stress occurs more often (ET/PET less than 1) on WD than on PD soils. Since the average county corn yield is based on all corn acreages in the county, regardless of soil types, how should a representative daily moisture stress variable for Tippecanoe County be calculated? Since about 43% of the corn in Tippecanoe County is grown on WD soils and about 57% on PD soils (Andresen, 1987, p. 127), the ET/PET ratios for the WD (Elston) and PD (Chalmers) SIMBAL estimates were weighted accordingly to estimate the daily ET/PET for Tippecanoe County.

Second, moisture stress can occur at any time during the season. In 1990, there was little stress. It occurred only for about a week after planting, and the corn yields in Tippecanoe County averaged 9.06 t ha^{-1} (145 bu a^{-1}). In 1991, there was considerable moisture stress, beginning even on the PD soil about 4 weeks before corn silking and continuing through grain maturity. Tippecanoe County corn yield was 4.75 t ha^{-1} (76 bu a^{-1}). Over what critical period should the daily ET/PET values be summed to obtain the most appropriate stress index for predicting final corn yield? The use of moisture stress indices for three different phenological periods (120, 90, and 37 days) was examined in this paper.

The interaction between weather and agricultural technology has always posed difficult problems, both in evaluating the effect of technology and in determining weather effects on crop yields. In wrestling with these problems before the eighties, Nelson and Dale (1978) found that the amount of fertilizer nitrogen (N) applied to corn land was a better covariable than trend (T). They used N as a marker for all technology, assuming that a farmer who used sufficient levels of N on corn land would also use sufficient levels of other fertilizers, appropriate corn hybrids, pesticides, and other crop management technologies. Since the mid 1980's, however, with increased environmental concern about nitrate leaching into the ground water, increased nitrogen prices, more efficient methods of N application, and the use of new corn hybrid varieties requiring less N, nitrogen application is no longer increasing in Indiana (Figure 2). Yet, corn yields maintained an upward trend through the eighties. Therefore, year (T), rather than N, was used as a linear technology covariate in the multiple regression model,

$$Y = \beta_0 + \beta_1 T + \beta_2 S_c + \epsilon, \qquad [1]$$

where Y is the average Tippecanoe County corn yield (Indiana Agric. Stat. Srvc, 1961-1990) in t ha^{-1}, T is year from 61 to 90, and S_c is the moisture stress index or the sum of the daily ET/PET values for the respective critical (c) phenological period, 120, 90, or 37 days. Because weather usually affects crop yields as an interaction with technology, not merely as a linear factor (Mach and Dale, 1985; Featherstone, *et al.,* 1991), a second regression model was investigated which included an interaction term ($T * S_c$),

$$Y = \beta_0 + \beta_1 T + \beta_2 S_c + \beta_3 (T * S_c) + \epsilon. \qquad [2]$$

Since final USDA corn yield estimates for Tippecanoe County were not yet available for 1991, these data could not be used in the regression analysis. Also, the data for 1970 were not used, the year a disastrous Southern Corn Leaf Blight was experienced in the eastern Corn Belt (Crane and Stierwalt, 1971). This left 29 years in the fitted regressions. Weighted S_c indices were also computed for 1970 and 1991, the years not used in the weather-technology-yield regressions, to create frequencies and cumulative fre-

Table 1. Summary regression statistics for models [1] and [2] for three different critical periods of moisture stress (S_c), n = 29, 1961-1990 excluding 1970.

Model [1] $Y = ß_0 + ß_1T + ß_2S + \epsilon$

S_c	F value*	Root MSE t ha	Adj R^2	C.V. %
S_{120}	25.6	0.86	0.64	13.0
S_{90}	27.0	0.85	0.65	12.8
S_{37}	30.3	0.81	0.68	12.3

Model [2] $Y = ß_0 + ß_1T + ß_2S_c + ß_3 (T * S_c) + \epsilon$

S_c	F value*	Root MSE t ha	Adj R^2	C.V. %
S_{120}	14.3	0.92	0.59	13.8
S_{90}	21.0	0.81	0.68	12.2
S_{37}	17.5	0.86	0.64	13.0

*All F values significant at $\alpha = 0.0001$.

quencies of the S_c indices for the 1961-1991 period. The empirical cumulative frequencies were estimated as m/(n + 1), where m is the rank of the respective S_c index from the lowest to the highest values and n is the number of years, 31 in this case. These empirical probability curves were also fitted with a beta distribution. Yao (1969) showed that the beta distribution,

$$F(X) = \frac{\Gamma(p)\ \Gamma(q)}{\Gamma(p+q)} \int_0^X X^{p-1} (1 - X)^{q-1} dX,\ 0 \leq X \leq 1,$$

provided excellent fits of the daily ratios of ET/PET. The parameter estimates of p and q were calculated from the average daily S_c indices by the method of moments and used to obtain the percentage probability points of the beta distribution tabled in the CRC Handbook (Beyer, 1968, pp. 251-265).

RESULTS AND DISCUSSION

Corn Yield, Technology, and Moisture Stress Relations. The summary regres-

Table 2. Regression coefficients (with their standard errors) for indicated model and critical period of moisture stress (S_c).

		Regression Coefficients for Model [1]					
S_c	Y-intercept	T(Year)		S_c			
S_{120}	-10.90**(±2.78)	0.12**	(±0.02)	0.076**	(±0.018)		
S_{90}	-10.39**(±2.34)	0.11**	(±0.02)	0.10**	(±0.02)		
S_{37}	-10.17**(±2.34)	0.13**	(±0.02)	0.22**	(±0.04)		
		Regression Coefficients for Model [2]					
S_c	Y-intercept	T(Year)		S_c		T*Sc	
S_{120}	-3.02 (±16.4)	0.025	(±0.20)	0.0028	(±0.15)	0.00091	(±0.0019)
S_{90}	12.78 (±13.2)	-0.19	(±0.17)	-0.19	(±0.16)	0.0038*	(±0.0021)
S_{37}	-3.75 (±14.2)	0.046	(±0.18)	0.026	(±0.42)	0.0024	(±0.0053)

* Significant at $\alpha = 0.15$.

** Significant at $\alpha = 0.0001$.

sion statistics for models [1] and [2], each for three different summation periods of S_c (S_{120}, S_{90}, and S_{37}) are shown in Table 1. The F-values for all six regressions shown in Table 1 were significant at the $\alpha = 0.0001$ level.

The models were associated with about 2/3 of the variance in the average county corn yield series (adjusted R^2 values ranged from 0.59 to 0.68). The summary statistics provide little help in selecting between models [1] and [2] and the two shorter stress periods. The adjusted R^2 values (0.68), root mean square errors (0.81 t ha^{-1} (13.0 bu a^{-1})), and the coefficients of variation (12.2, 12.3 percent) were almost identical for [1] with S_{37} and [2] with S_{90}.

The estimated regression coefficients with their standard errors are shown in Table 2 for the six regressions. All of the coefficients for [1] were significant at $\alpha = 0.0001$. There was no significant correlation between S_c and T and, thus, no problem with multicollinearity. When the interaction term was included, only the coefficient for the interaction term in [2] for S_{90} was significant at $\alpha = 0.15$. Multicollinearity (high correlation between the linear terms and their products) causes overestimates of the standard errors of the coefficients (Green, 1978, p. 226) but does not bias the estimates. Perhaps, more definitive results should not be expected when using a county average corn yield for the Y variable, a simple trend variable (T) to represent all technology, and precipitation from a single weather station to estimate the weighted S_c for the county.

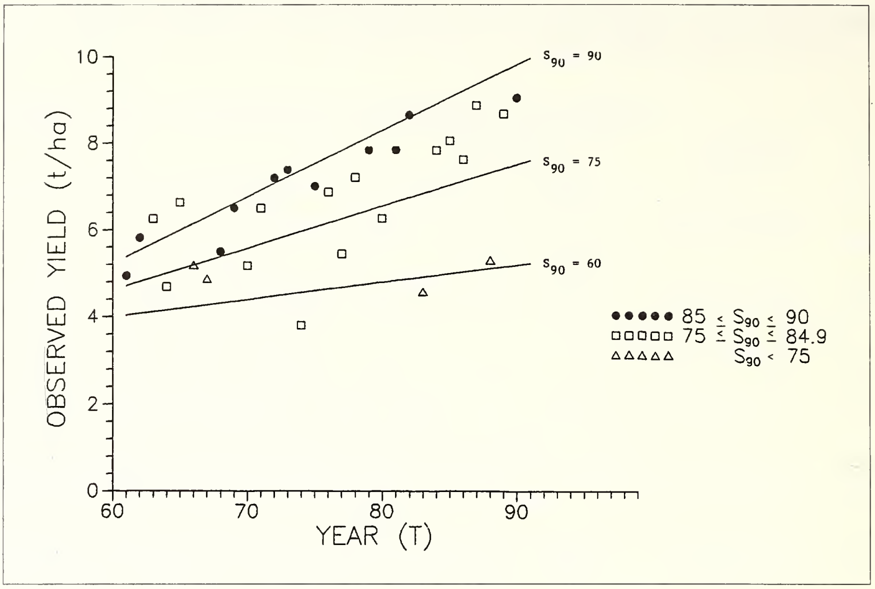

Figure 3. Average Tippecanoe County corn yield plotted on year with indicated category of moisture stress (S_{90}) experienced during the 90-day period from 39 days before to 50 days after silking in that year. Solid lines are [3] evaluated of S_{90} levels of 90 (none), 75 (moderate), and 60 (severe moisture stress).

Model [2] for S_{90} is reproduced from Table 2 as [3],

$$Y = 12.78 - 0.19\,T - 0.19\,S_{90} + 0.0038\,(T * S_{90}), \qquad [3]$$

and also in Figure 3, arbitrarily evaluated for S_{90} values of 90, 75, and 60 on the scattergram of average Tippecanoe County corn yields on year. The S_{90} value of 90 is a bound of no moisture stress, 60 is just below the lowest value (highest stress) observed in the 31-yr period (61.8 in 1988), and 75 is halfway between. The 75 and 60 values can be considered moderate and severe moisture stress, respectively.

The interaction model [3] in Figure 3 shows increasing variability in average corn yields. While agricultural technology continues to increase the yield potential with favorable weather, yields are still severely reduced with insufficient precipitation. For example, note that the yields in 1983 and 1988 were below those in the 60's. Technology has increased yields an estimated 0.15 t ha^{-1} yr^{-1} (2.4 bu a^{-1} yr^{-1}) if there were no moisture stress (S_{90} = 90), but only 0.04 t ha^{-1} yr^{-1} (0.6 bu a^{-1} yr^{-1}) with severe moisture stress (S_{90} = 60). With 1990 technology (T = 90), each deficit unit of S_{90} (ET/PET) reduces the average county corn yield 0.15 t ha^{-1} (2.4 bu a^{-1}).

For the 37-day stress period, the interaction term was not significant, and model [1] with S_{37} is reproduced from Table 2 as [4],

$$Y = -10.17 + 0.13\,T + 0.22\,S_{37}, \qquad [4]$$

and also in Figure 4, evaluated for arbitrary S_{37} values of 37, 30, and 23 on the scattergram of average county corn yields on year. Again, 37 is the bound of no mois-

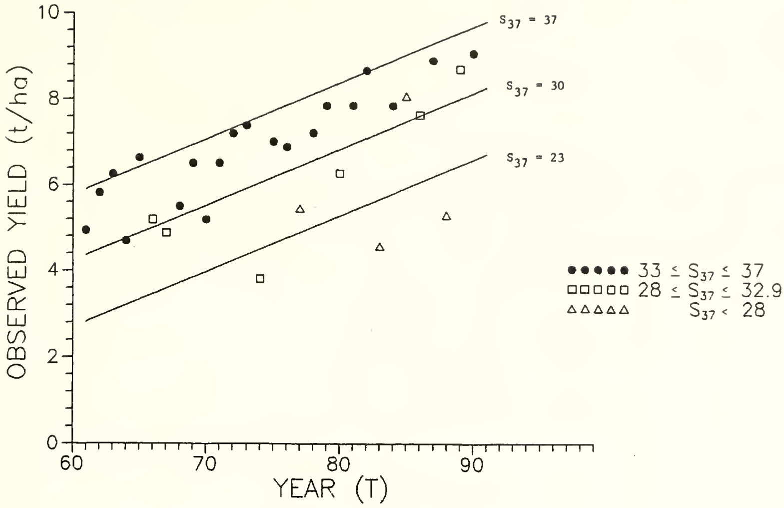

Figure 4. Average Tippecanoe County corn yield on year with each yield plotted with indicated category of moisture stress (S_{37}) experienced in that year during the 37-day period from 16 days before to 20 days after silking. Solid lines are [4] evaluated for S_{37} levels of 37 (none), 30 (moderate), and 23 (severe moisture stress).

ture stress, 23 is just above the lowest value observed (22.4 in 1991), and 30 is half way between. The linear variable model [4] shows that technology increased yields an average of 0.13 t ha^{-1} yr^{-1} (2.1 bu a^{-1} yr^{-1}) independent of moisture stress. Each deficit unit of S_{37} (ET/PET) decreased the average corn yield 0.22 t ha^{-1} (3.5 bu a^{-1}) independent of technology. Only further testing of [3] and [4] with independent data will determine their relative predictive abilities, but certainly weather remains a major source of the variability in corn yields.

In 1991, the S_{90} index was 65.9. With [3] and T = 91, the predicted average corn yield for Tippecanoe County is 5.76 ± 0.81 t ha^{-1} (92.2 ± 13.0 bu a^{-1}), down 41% from the potential 1991 yield of 9.50 t ha^{-1} (152.0 bu a^{-1}) with S_{90} = 90. The S_{37} index in 1991 was 22.4, the lowest in the 1961-1991 record. If this index were used in [4], again with T = 91, the predicted Tippecanoe County average corn yield in 1991 is estimated at 6.59 t ha^{-1} (105.4 bu a^{-1}), down 33% from the potential 1991 yield of 9.80 t ha^{-1} (156.8 bu a^{-1}) with S_{37} = 37.

The advantage of using S_{37} and [4] is that a preliminary prediction of the 1991 crop yield could be made 20 days after corn silking (Table 3) or on 27 July 1991. If S_{90} and [3] were used, the prediction could not be made until 50 days after silking or on 26 August 1991, when the corn grain filling period was essentially completed. With the corn growing season over, model [3] with S_{90} should give the best prediction, recognizing that the prediction goes beyond the data range used for T in both models and for S_{37} in [4]. The preliminary USDA 1991 estimated corn yield for Tippecanoe County was 4.75 t ha^{-1} (76 bu a^{-1}), less than both [3] and [4] estimates.

Climatology of Moisture Stress. The unweighted stress indices (S_c) for the PD

Table 3. Moisture stress indices for both poorly-drained (Chalmers) and well-drained (Elston) soils, and the weighted average for 120-, 90-, and 37-day periods during the indicated growing season in Tippecanoe County, Indiana, 1961-1991. The county average corn yield and the average date of corn silking are also shown for each year.

Year	Average Yield t ha^{-1}	Silk Date	Stress Indices: Chalmers PD 120D	Chalmers PD 90D	Chalmers PD 37D	Elston WD 120D	Elston WD 90D	Elston WD 37D	Weighted Average 120D	Weighted Average 90D	Weighted Average 37D
61	4.94	8/07	119.1	89.0	36.2	108.5	80.8	32.4	114.5	85.4	36.8
62	5.81	7/21	119.1	89.4	37.0	112.4	83.8	36.5	116.2	86.9	36.7
63	6.25	7/30	117.1	87.1	35.6	107.1	77.6	32.0	112.8	83.4	36.5
64	4.69	7/19	111.4	82.0	34.9	96.9	70.7	30.5	105.7	77.3	33.3
65	6.63	7/24	115.8	85.8	36.1	106.8	77.9	32.3	112.0	82.4	34.2
66	5.19	7/28	103.3	73.8	29.4	84.4	57.8	22.7	91.5	64.0	28.0
67	4.88	8/01	103.8	73.9	30.1	84.9	57.4	23.0	94.6	67.5	28.9
68	5.50	7/29	119.6	89.6	36.6	116.1	86.2	34.3	118.1	88.6	36.2
69	6.50	7/27	119.5	89.5	36.5	112.8	83.2	33.5	116.3	86.5	35.3
70	5.19*	7/27	117.8	87.8	36.0	108.3	78.6	32.4	113.7	83.8	34.6
71	6.50	7/24	118.6	89.1	36.9	106.5	79.5	35.5	113.4	84.8	36.2
72	7.19	7/26	118.4	89.2	36.8	109.5	83.4	34.1	114.6	86.7	35.9
73	7.38	7/28	119.2	89.2	36.3	111.9	82.4	32.7	116.0	86.2	35.1
74	3.81	8/09	111.6	81.6	30.6	99.0	70.1	23.1	108.1	78.3	31.0
75	7.00	7/16	119.1	89.2	36.7	111.2	82.5	32.8	115.7	86.3	35.3
76	6.87	7/21	114.1	84.4	35.7	98.9	71.1	30.9	107.2	78.4	33.6
77	5.46	7/13	109.7	81.4	29.9	94.5	70.8	21.7	103.2	76.5	26.4
78	7.21	7/26	119.4	89.4	36.9	107.7	78.9	33.9	113.5	84.5	35.3
79	7.84	7/25	119.0	89.3	37.0	111.9	84.6	36.9	115.6	87.0	37.0
80	6.27	7/18	114.9	85.1	33.2	104.1	75.2	26.3	110.3	80.9	30.3
81	7.84	7/31	119.5	89.9	36.9	112.4	83.3	35.6	116.7	88.6	36.9
82	8.65	7/15	117.4	89.2	36.6	105.9	79.5	33.1	112.2	86.9	35.1
83	4.58	7/26	96.6	74.7	26.8	79.6	57.2	20.5	92.1	62.6	23.1
84	7.84	7/24	109.2	83.8	36.5	82.6	66.3	30.4	102.1	77.6	33.2
85	8.06	7/15	104.0	79.0	27.9	88.4	70.5	23.1	97.3	75.3	25.8
86	7.62	7/16	113.1	83.1	34.9	101.7	72.1	29.7	108.2	78.4	32.7
87	8.88	7/07	109.4	85.1	35.1	94.8	77.2	31.7	103.1	81.7	33.6
88	5.31	7/19	79.7	64.6	28.3	64.0	58.2	27.2	72.9	61.8	27.8
89	8.69	7/24	111.1	81.6	32.5	93.7	68.1	25.9	103.6	75.8	29.7
90	9.06	7/24	119.1	89.3	36.8	114.0	85.8	36.0	116.9	87.8	36.5
91	4.75**	7/07	101.1	71.1	25.6	87.8	58.9	18.2	95.4	65.9	22.4

* Southern Corn Leaf Blight epidemic; not used in regression (Crane and Stierwalt, 1971).

** Preliminary USDA estimate; not used in regression.

and WD soils for the three critical periods for Tippecanoe County are shown in Table 3 for each year from 1961 through 1991, together with the weighted average stress indices for the county, the date by which 50% of the corn had silked in the county, and the respective average county corn yields. The weighted S_{37} value of 22.4 in 1991 was the

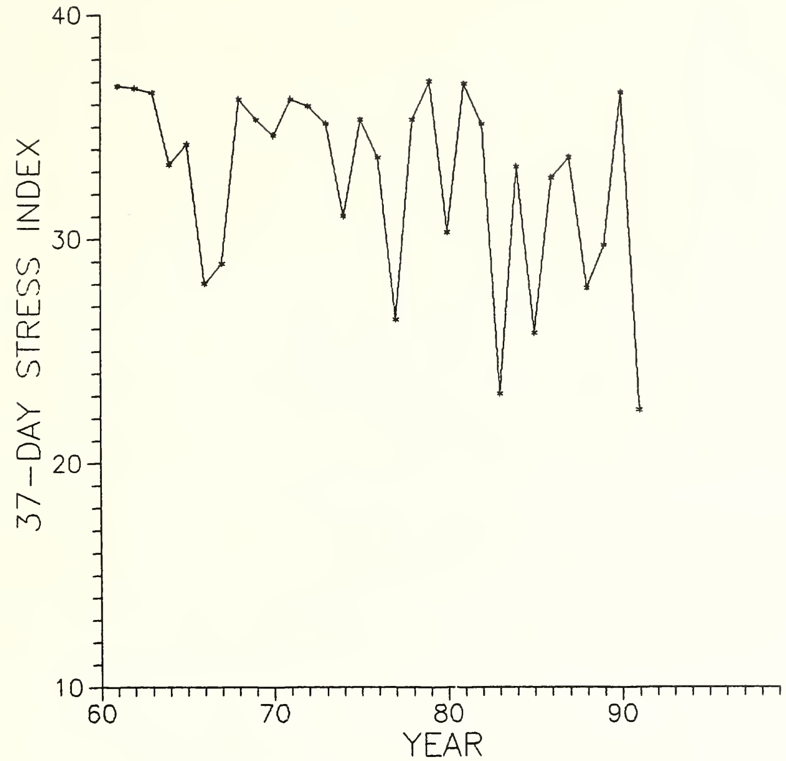

Figure 5. Weighted 37-day moisture stress index for Tippecanoe County on year, 1961-1991.

lowest (greatest stress) in the 1961-1991 period, but the lowest value (greatest stress) for both S_{120} (72.9) and S_{90} (61.8) occurred in 1988.

The weighted S_{37} indices (0.57 $S_{37\,PD}$ + 0.43 $S_{37\,WD}$) for Tippecanoe County are plotted for each year in Figure 5. While there may appear to be more stress in the eighties, the 1961-1991 series is too short for any conclusions about a changing climate. The correlation coefficient of S_{37} on T is -0.32, not significant at the a= 0.05 level. For probability prediction purposes, the climatology of this 31-year period is assumed to be representative of the weather to come.

The frequency distribution (Figure 6) for the weighted S_{37} indices for the 1961-1991 period shows high negative skewness. Only one year had an S_{37} value less than 23, and 14 of the 31 years had S_{37} values greater than 35. Since S_{37} is included in S_{90} and S_{120}, the three stress indices are highly correlated, e.g., the correlation between S_{37} and S_{90} is 0.88. Therefore, the frequencies for the S_{90} and S_{120} indices show the same highly skewed pattern as Figure 6, there being a greater probability for low moisture stress or "favorable weather" than for high moisture stress in Tippecanoe County, Indiana. Frequencies prepared from the unweighted S_c indices in Table 3 show the skewness for the stress

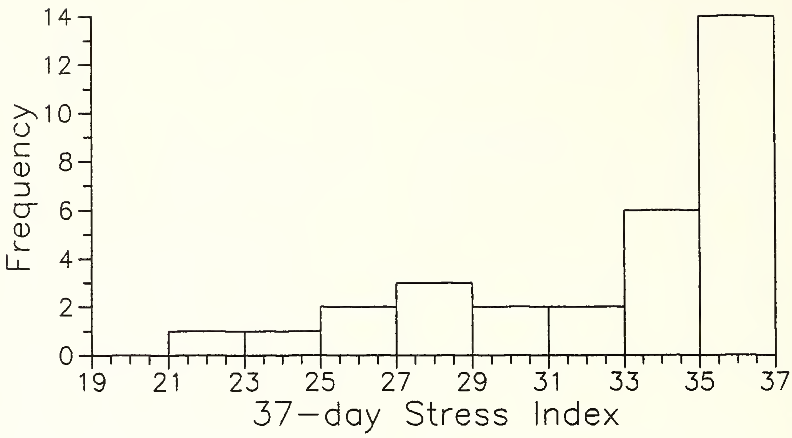

Figure 6. Frequency distribution of weighted 37-day moisture stress index for Tippecanoe County, 1961-1991.

indices on just PD soils greater, and for just WD soils lesser, than for the weighted stress indices.

The cumulative frequencies for S_{90} and S_{37} shown in Figure 7A and B, respectively, provide an estimate of the probability of having at least the indicated level of moisture stress in Tippecanoe County, again assuming that the last 31 years are a representative sample of the weather to come in the next few years. Both the empirical and fitted beta distribution curves are shown. (The moment estimates of the parameters in the beta distribution for S_{90} were $\hat{p} = 10.95$ and $\hat{q} = 1.38$, and for S_{37}, $\hat{p} = 6.99$ and $\hat{q} = 0.88$.) From Figure 7B, the beta distribution probability of having an S_{37} value less than 34 next year, or any year, is 50%. Using [4], T = 92 (forecasting beyond the sample data range of T) and $S_{37} = 34$, the estimated corn yield in 1992 is 9.3 t ha^{-1} (149 bu a^{-1}). Thus, the probability of having an average Tippecanoe County corn yield less than 9.3 t ha^{-1} is about 50% or, conversely, the probability of having a yield of 9.3 t ha^{-1} or greater is 50%.

Similarly, the climatology of moisture stress shown in Figure 7A for S_{90}, preferred because S_{90} includes critical growth and development stages before S_{37} as well as the whole corn grain filling period, can be used with [3] and T = 92 to convert and double label the 90-day stress index abscissa to corresponding average county corn yields. Although the 90 S_{90} bound imposes a predicted yield bound in 1992 of 9.7 t ha^{-1} (155 bu a^{-1}) and the averaging process of the regression method decreases the predicted yield variability, the Figure 7A agroclimatology certainly provides a better estimate of the skewed corn yield distribution than a straight frequency of the heterogeneous 1961- 1991 yield series. Thus, the Figure 7A curve indicates that the probability of having an average county corn yield less than 5 t ha^{-1} (80 bu a^{-1}) is about 2%, and the probability of having a yield less than 8 t ha^{-1} (128 bu a^{-1}) is about 42%.

The agroclimatology of moisture stress and predicted corn yield is conditioned upon the accuracy of [3] and [4], SIMBAL, the representativeness of the measured precipitation used to model ET/PET for the county, the ability of the S_c and T variables to repre-

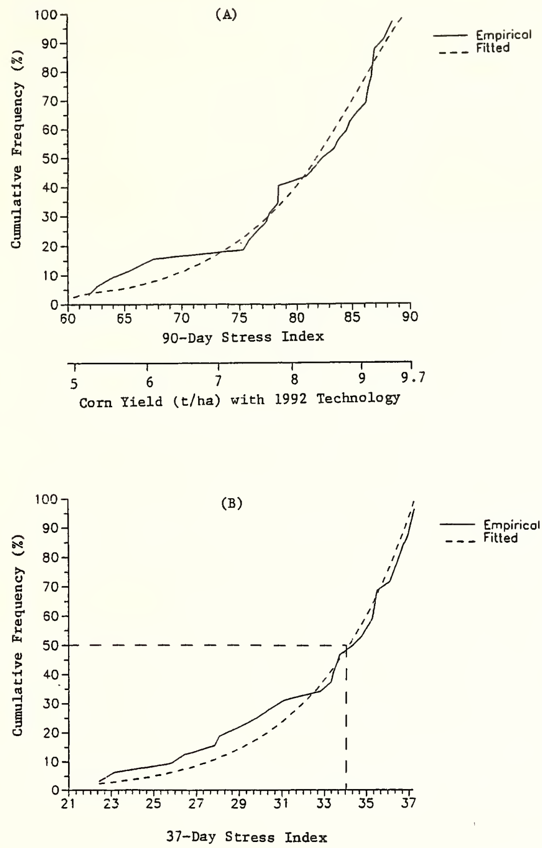

Figure 7. **A.** Empirical and fitted beta distribution probability of having at least indicated level of weighted moisture stress index for the 90-day period in Tippecanoe County, Indiana, based on 1961-1991 record. The second abscissa, labeled in t ha^{-1}, provides the probability of having at least the indicated average corn yield in 1992, estimated with [3] and T = 92. **B.** Empirical and fitted beta distribution probability of having at least the indicated level of weighted moisture stress index for the 37-day period in Tippecanoe County, Indiana, based on the 1961-1991 record. The rectangular dashed lines show that the beta distribution probability of having a moisture stress index less than 34 is 50%.

sent the major environmental and technological effects on corn yields, and finally the accuracy of the county average corn yield estimates by the Indiana Agricultural Statistics Service.

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