A Methodology for Considering the Effect of Weather on the Response of Corn Yields to Added Fertilizer: A Case Study in Indiana with Nitrogen

MICHAEL A. MACH and ROBERT F. DALE
Purdue University, West Lafayette, Indiana 47907

Introduction

Many studies have shown that that crop yield response to applied fertilizer is greatly influenced by weather and climate (Dale and Shaw, 1964; Voss, Hanway, Fuller, 1970; Bondavalli, Colyer, and Kroth, 1970; Isfan, 1979; and Shaw, Ross, and Meyers, 1980). Yet, in most agricultural experiments, weather is rarely considered quantitatively in the analysis and interpretation of results. If the experiment has been conducted over several years and/or locations, the cumulative effect of weather on yield has been pooled with the effects from other unexplained sources of variation and usually attributed in analyses of variance to Years and/or Locations, and their interactions with Treatments. Rising costs of crop production, especially in nitrogen fertilizers (Hargett and Berry, 1980), and decreasing returns to the farmer dictate the need for quantifying the interactions between various management and weather variables affecting crop production to allow for more intelligent management decisions.

The three most important weather variables affecting crop growth and final yields are light, temperature, and plant moisture (Cowan and Milthorpe, 1968). Coelho and Dale (1980) considered all three weather variables on each day, as they affect corn (Zea mays L.) growth, in a single environmental product, called the Energy-Crop Growth (ECG) variable.

$$ECG = (SR/L)(FLAI)(ET/PET)(FT) \quad (1)$$

SR is the daily solar radiation or short wave energy received on a horizontal surface, L is the latent heat of vaporization of water, LAI is the corn leaf area index, and FLAI is 1-exp(-0.79 LAI), used to convert the SR to that intercepted by the corn canopy. ET/PET is the ratio of actual to potential evapotranspiration, and FT is a temperature function reflecting the growth rate of corn relative to the maximum obtained from 28 to 32°C. Except for SR and L, all factors in (1) range from 0 to 1, which puts the units of ECG into cm of water evaporated if all of the intercepted short wave energy were converted to latent heat.

Coelho and Dale (1980) also found that FT alone, computed from the daily maximum and minimum temperatures and summed from date of planting (ΣFT), provided a slighly better estimate of the experimental corn ontogeny than that obtained using modified (10-30°C cutoff) growing degree days. For example, at ΣFT = 3 about 50% of the corn plants emerged, at ΣFT = 13 the growing point of the corn plants were rising above the soil surface, and at ΣFT = 37, about 50% of the corn plants were silked. By summing the daily ECG (1) over several different vegetative growth and grain filling periods, Mach (1982) found that the sum of the daily ECG from the date ΣFT = 13 (39 to 45 days before silking) to 50 days past silking provided the energy-crop growth index (ΣECG) most highly correlated with final grain yields. The basis for the ECG is that with ample solar radiation upon a corn canopy which completely covers the soil surface (FLAI = 1), with no plant moisture stress (ET/PET = 1), and with temperature at the

optimum for plant growth (FT = 1), the corn will make excellent growth. The greater the ΣECG, the greater will be the corn growth and final yield.

The objective of this paper is to demonstrate the use of ΣECG to quantify the effect of weather on the response of corn to added nitrogen fertilizer. To do this, we have used data from a long-term nitrogen (N) fertilizer field trial with corn evaluating the yield responses for selected corn hybrids and application methods.

Materials and Methods

A long term N fertility management trial was conducted by Dr. Stanley Barber and Mr. Robert Austin from 1966 through 1981 on a Raub silt loam (Aquic Arguidoll) at the Purdue University Agronomy Farm. Raub developed on Wisconsin till, is poorly-drained with 0-1% slope, and has an organic matter content of about 3.5%. A number of full-season corn (Zea mays L.) hybrids were planted in 71-cm rows at a population density of about 54,560 plants per hectare throughout the experimental period. Each experimental plot was six rows wide and 21 m long. The specific corn hybrids used and the dates of planting for each year are shown in Table 1.

Nitrogen rates and application methods were replicated three times. The source of fertilizer N was ammonium nitrate in the early years and urea in the later years, except for the fall application of anhydrous ammonia, knifed in between the rows after harvesting. The application methods and rates of fertilizer N used in the experiment are shown in Table 2. The spring broadcast treatments were applied before planting. Check plots, which received no nitrogen, were also included each year. Corn grain yields for each experimental plot were determined from a 15-m length of the two center rows and expressed in kg/ha at 15.5% moisture. Since it took at least the first four years of the field trials for the corn yields to reach equilibrium levels on the low fertility treatments (0, 67 Kg N/ha), the 1966-1969 (SX-29) yields were not used in this paper.

Weather data necessary to calculate the components in ECG on a daily basis—solar radiation (SR), maximum and mimimum air temperatures used to compute FT, precipitation, and pan evaporation—were available from the

TABLE 1. *Corn hybrid, year planted, and date of planting in the long-term fertility management experiment, Field 54, Purdue University Agronomy Farm.*

CORN HYBRID	YEAR	PLANTING DATE
P-A-G SX29	1966	26 May
	1967	19
	1968	7
	1969	23
Pioneer 3369A	1970	19
	1971	20 Apr
	1972	18 May
	1973	14
	1974	6
	1975	8
	1976	23 Apr
AGRI 777	1977	11 May
Beck 65X	1978	31
	1980	6
	1981	1 Jun
Pioneer 3183	1979	10 May

TABLE 2. *Application method and Nitrogen source and rates of fertility used in the long-term fertility management experiment, Field 54, Raub silt loam, 1966-1981, Purdue University Agronomy Farm.*

APPLICATION METHOD AND N SOURCE	N FERTILITY RATE (kg/ha)
Fall Anhydrous Ammonia (1966-1978)	67,134,202
Fall Broadcast (ammonium nitrate or urea)	67,134
Spring Broadcast (ammonium nitrate or urea)	67,134,202
Spring Broadcast on even years (ammonium nitrate or urea)	134,269,403

cooperative National Weather Service-Purdue University weather station, located about 700 m south of the fertility experiment. The soil moisture model for poorly drained soils described by Dale et al. (1982) was used to obtain the daily estimates of ET/PET required in (1), assuming the soil moisture characteristics for Raub silt loam approximated those for Chalmers silt loam. Leaf area measurements were not taken in the long term fertility experiment, and it was necessary to estimate LAI to obtain the FLAI term in ECG. This was done with a model modified from that described by Dale, Coelho and Gallo (1980) for corn on high fertility soils. The algorithm used to predict the maximum leaf area per plant (LAMAX) was changed from a simple linear function of plant population density (P) to a function of P and its interaction with nitrogen rate (N): LAMAX = 0.834 -0.00578 P + 0.0000157 N X P. This function was developed with leaf area measurements made on these same fertility plots in 1978 and 1979 by Walburg et al. (1982) and in 1982 by J. P. McGarrahan and T. K. Flesch of the Agronomy Department, Purdue University.

Multiple regression models used in this study were of the general form:

$$Y = \beta_0 + \Sigma\beta_i X_i + \epsilon, \qquad (2)$$

where Y is the experimental corn grain yield for a given treatment-year β_0 and β_i are the regression coefficientes, X_i the independent variables, and ϵ the random error. The independent variables considered in this study were nitrogen rate (N), N^2, ΣECG, and the interaction, N X ΣECG, where Σ ECG is the sum of daily values (1) from ΣFT = 13 to 50 days after silking. The regression coefficients in (2) were fitted with computer programs from the Statistical Package for the Social Sciences (SPSS15) at the Purdue University Computing Center.

Results and Discussion

The average yields for all corn hybrids for the indicated N rate within each of the application methods, 1970-1981, are shown in Figure 1. The weather, however, causes year-to-year variability from these average yield responses to N (Broadbent, 1980). For example, for Pioneer Hybrid 3369A 28 sets of observations (7 years, 4 nitrogen treatments) were available to examine the N X ΣECG interactions for both the spring broadcast and fall anhydrous applications. A scatter diagram of Pioneer 3369A corn yield on ΣECG for each of the years and N levels is shown in Figure 2. At the 0 and 67 kg N/ha levels for the spring broadcast application there is little response to "better weather" as identified by greater ΣECG. At the 134 and 202 kg N/ha levels, however, there is a definite trend toward increasing yields with increasing ΣECG, as also shown on Figure 2 by the regressions fitted to the data and evaluated at 0, 67, 134, and 202 kg/N/ha.

Of the regression models examined by Mach (1982) the model $Y = b_0 + b_1N + b_2N^2 + b_3N \times \Sigma ECG$ consistently gave greater coefficients of determination (R^2) and F values, as well as the most consistent regression patterns. All regression coefficients and models were significant at the $\alpha = 0.05$ level. Because the linear ΣECG term is included only in the interaction term, the predicted slope of Y on ΣECG for N = 0 is necessarily 0. The quadratic form of the yield response to N can be seen in the greater yield increase from 0 to 67 kg N/ha from 67 to 134 and 134 to 202.

The increasing yield response to ΣECG at higher N is also evident in Figure 3 for the fall anhydrous ammonia application. The fitting of the quadratic model with the observational data, however, causes the predicted yields for the N = 202 level to be below those for the 134 level, except at greater ΣECG. In fact, the regression model shown in figure 3 provides a maximum predicted corn yield at 162 kg N/ha with ΣECG = 38 and at 125 kg N/ha with ΣECG = 28.

The scatter diagram of corn yields on ΣECG for the indicated year and N rate for the fall broadcast treatment is shown in Figure 4. There seems to be little yield response to ΣECG at any N level. The yield increases were attributed to increases in nitrogen rate. Some environmental or biotic factor was more influential in determining yield than the ΣECG variable, especially in 1973, which had the lowest yield and highest ΣECG. The mean yield level for N = 134 in Figure 4 is below that

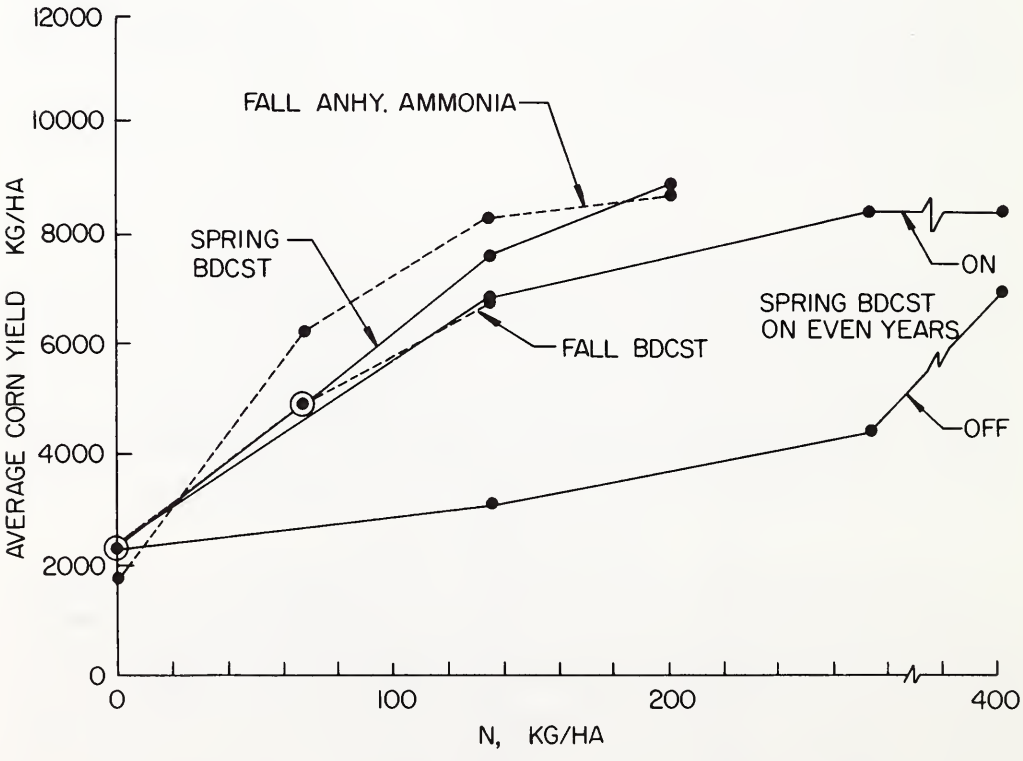

FIGURE 1. *Average response of corn yield to nitrogen rate (N) for indicated application method, 1970-1981, except fall anhydrous ammonia, 1970-1978, Raub silt loam, West Lafayette, Indiana. For the spring broadcast every other year, "ON" is the average yield for the years in which the fertilizer was applied, "OFF" for the years in which it was not applied.*

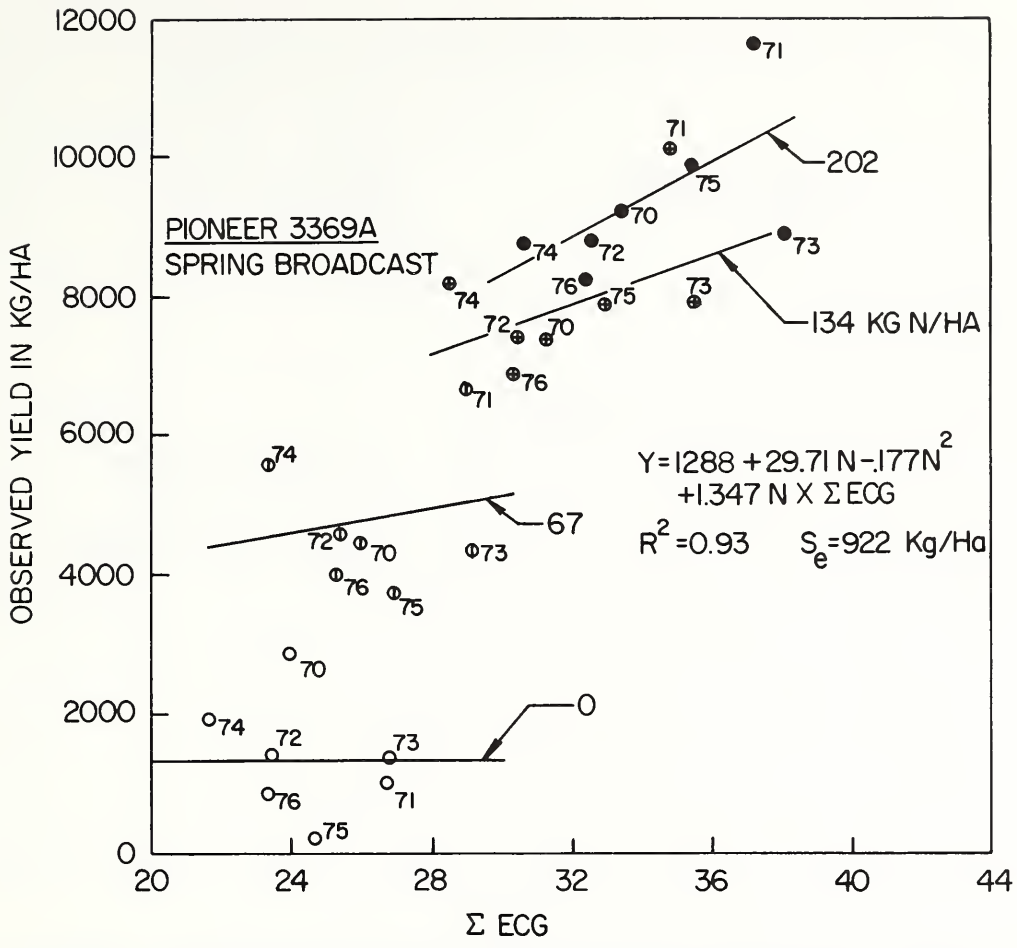

FIGURE 2. *Scatter diagram and regression fitting of corn yield on the energy-crop growth index (ΣECG) and indicated nitrogen rate (N), N applied by broadcasting ammonium nitrate or urea in the spring for the indicated year, Pioneer hybrid 3369A on Raub silt loam, West Lafayette, Indiana. The plotted numbers and symbols provide the year and N level for the experimental yield, e.g. open circles are O N, solid circles 202 kg N/ha.*

in Figures 2 and 3, suggesting that considerable nitrogen had been lost between the fall broadcast application and the period of vegetative corn growth the following spring (Stevenson and Baldwin, 1969). Welch et al. (1971) reported that excess water creates anaerobic conditions favorable for denitrification and that leaching also occurs when water percolates through the soil profile. Volatilization and leaching losses of the surface ammonium nitrate of urea can be affected by different weather conditions anytime from the nitrogen application to the beginning date for summing ECG, about 39 to 45 days before silking. Thus, the experimental N levels may not be as representative of the nutrient availability for the fall broadcast application as those for the fall anhydrous and spring broadcast applications.

Although there may be corn hybrid X nitrogen rate X weather interactions, the yields from all corn hybrids were pooled from 1970 within each of two application methods, fall anhydrous ammonia and spring broadcast. The regression model was fitted to the observed ΣECG, N, and corn yield data for each of these

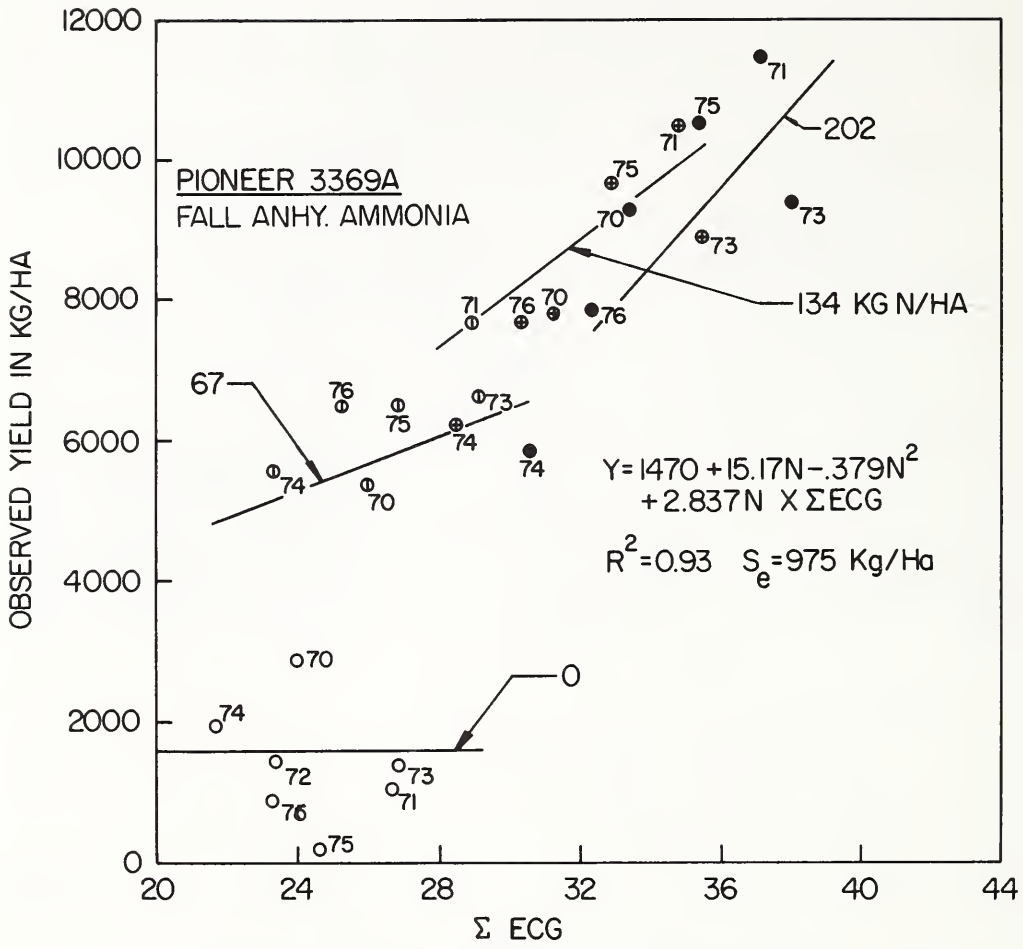

FIGURE 3. *Scatter diagram and regression fitting of corn yield on the energy-crop growth index (ΣECG) and indicated nitrogen rate (N), N applied by knifing in anhydrous ammonia the previous fall for indicated year, Pioneer hybrid 3369A on Raub silt loam, West Lafayette, IN. Plotted years and symbols same as Figure 2.*

management systems. In Figure 5 the observed yields were plotted against those estimated (predicted) for the fall anhydrous application, 1970-1978. The R^2 was 0.91, with the standard error 1010 kg/ha. Because there is no linear ΣECG term in the model, all of the predicted yields at N = 0 are at b_0.

The same regression model for the fall anhydrous application was used to predict yield for the indicated N at two levels of ΣECG, 28 and 38, "poor and good weather" years, respectively, as shown in Figure 6. These two curves generally bracket the overall average yields, reproduced from Figure 1 as the solid circles. The quadratic form of the model, previously discussed with the Pioneer 3369A results shown in Figure 3, indicates that corn yields predicted for any N with ΣECG = 38 were above those with ΣECG = 28, the difference increasing to a maximum of about 3800 kg/ha at the highest N level (202 kg N/ha). The yield response curve for ΣECG = 28 maximized at lower N than that for ΣECG = 38.

The regression model for the pooled corn hybrids for the spring broadcast application, 1970-1981, are also shown in Figure 6, evaluated for ΣECG = 28 and 38. Both curves are below those for the fall anhydrous application except at higher N and lower ΣECG values. The spring broadcast model does not reach a max-

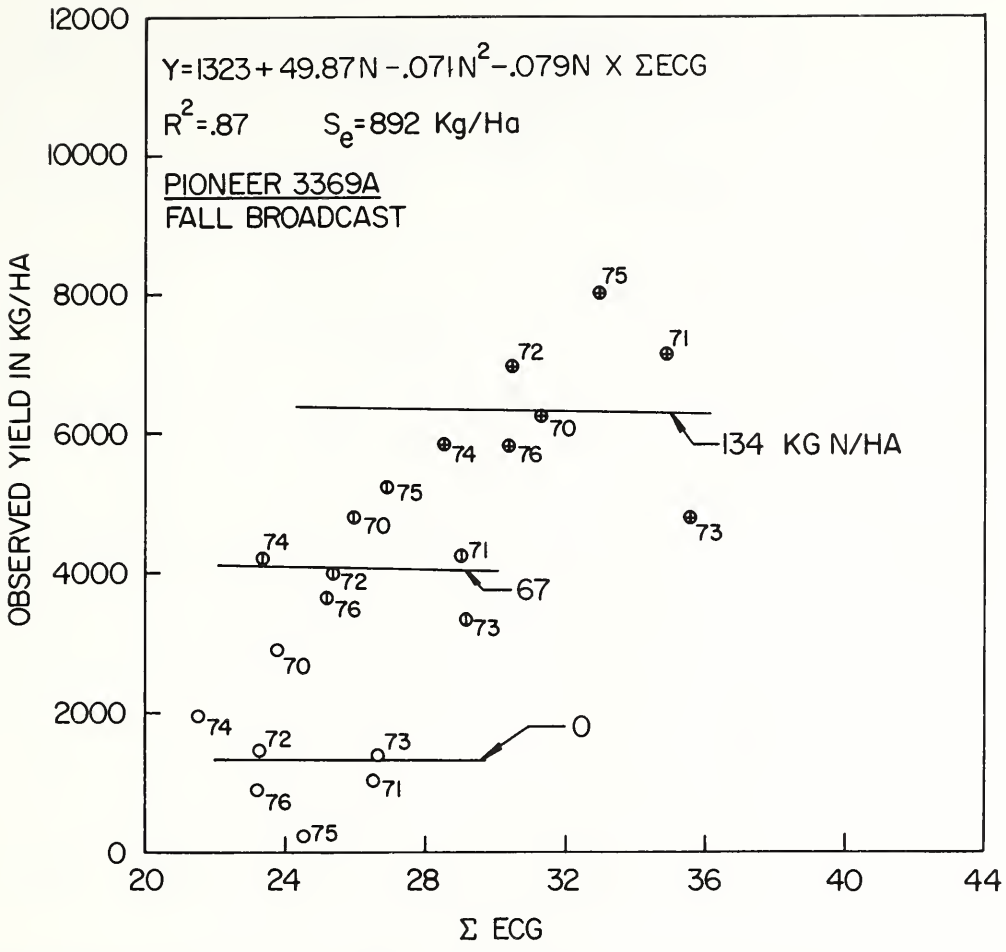

FIGURE 4. *Scatter diagram and regression fitting of corn yield to the energy-crop growth index (ΣECG) and indicated nitrogen rate (N), N applied by broadcasting ammonium nitrate or urea in the previous fall for the indicated year, Pioneer hybrid 3369A on Raub silt loan, West Lafayette, Indiana. Plotted years and symbols same as Figure 2.*

imum yield within the experimental N rates. The spring broadcast curves show less difference in yield response to N under low and high ΣECG than do the fall anhydrous curves.

Conclusion and Recommendation

A methodology for identifying weather influences on corn yield as a single energy-crop growth index, ΣECG, has been demonstrated and used to interpret corn yields from long-term fertility trials. Greater yield responses to increased levels of nitrogen fertilization occurred with higher than with lower ΣECG. Many improvements in the methodology could be made. First, some additional environmental measure of occurrences of warm weather, heavy rains, and other conditions known to be conducive to nitrogen losses from the time of fertilizer application through the vegetative growth period should be considered, especially when comparing fall with spring broadcast applications. Second, in this study corn growth was assumed to be equally responsive to ECG throughout the period

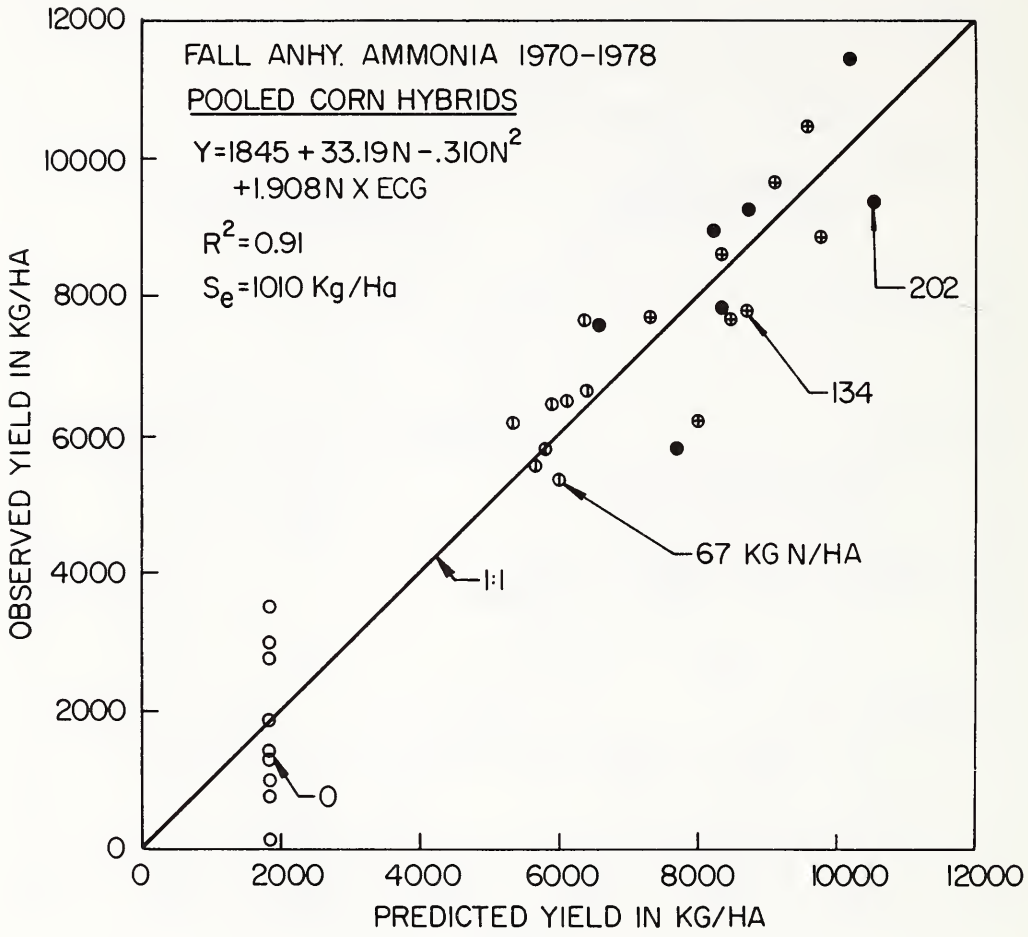

FIGURE 5. *Observed corn yield on that predicted with indicated regression equation and nitrogen rate (N), N applied by knifing in anhydrous ammonia the previous fall, for all hybrids used, 1970-1978, Raub silt loam, West Lafayette, Indiana.*

from ΣFT = 13 (39-45 days before silking) to 50 days past silking. Coelho and Dale (1980) showed this is unlikely. Weighting the components in ECG differently, such as weighting temperature heavier than solar radiation during the vegetative growth period and solar radiation heavier during the grain filling period, should be considered. Third, errors in measuring or estimating any of the ECG components for the field trials are multiplied in the ECG product variable. Finally, the ET/PET factor in ECG only provides "positive" plant moisture stress. "Negative stress", or too much water, may also be a significant factor in the early spring and should be examined.

Notwithstanding these self-critical statements, we suggest that the energy-crop growth variable may be useful in interpreting the effect of weather on corn yield response to nitrogen application in a set of long term fertility trials. The use of such a weather variable provides a means for pooling experimental data over years and locations to increase the range in the weather, crop variety, soil, nitrogen, and yield data, thereby increasing the inference space of the research results and expanding the soil-climate areas in which the results are pertinent.

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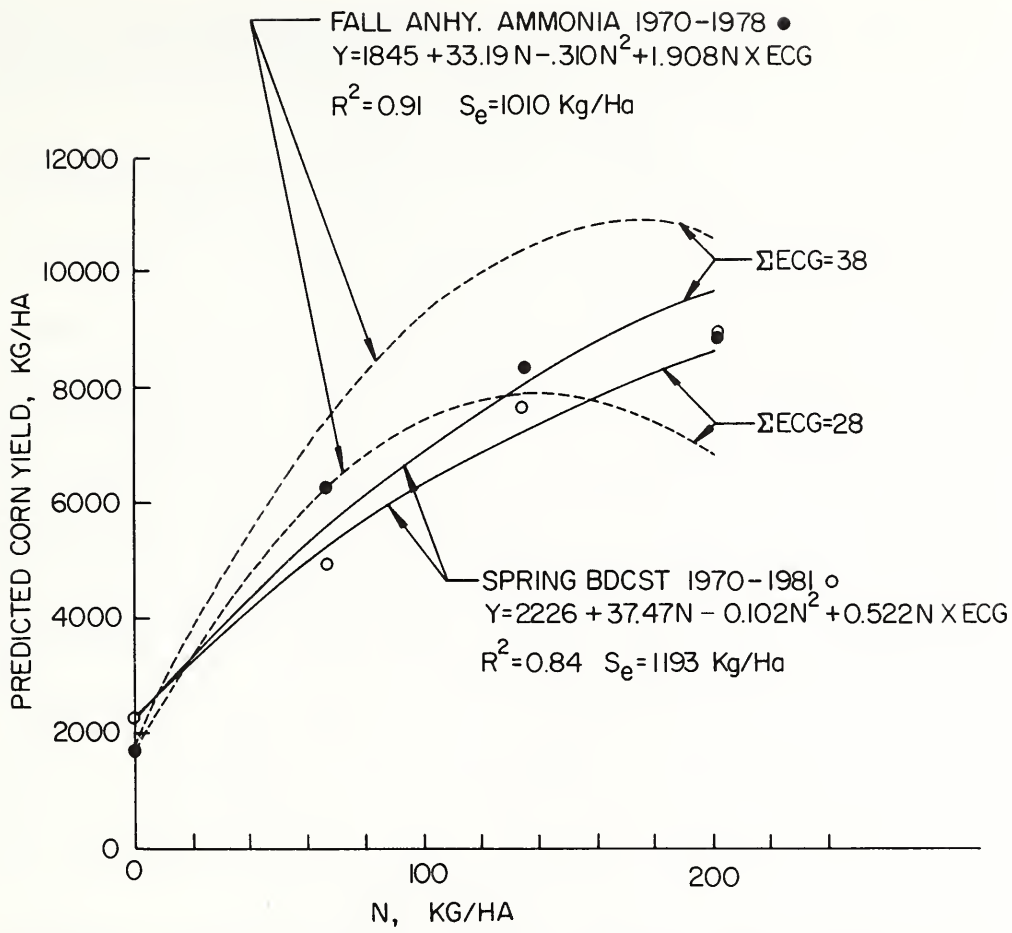

Figure 6. *Predicted corn yields on nitrogen rate (N) for two levels of the energy crop growth index, ΣECG = 38 ("good weather") and ΣECG = 28 ("poor weather"), and two application methods, fall anhydrous ammonia (1970-1978) and spring broadcast of ammonium nitrate of urea (1970-1981) for all hybrids used, Raub silt loam, West Lafayette, Indiana. The average yields for the indicated N rate have been reproduced from Figure 1, solid circles denoting fall anhydrous and open circles spring broadcast.*

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