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RELATIONSHIPS BETWEEN CLIMATE AND CROP YIELDS IN MICHIGAN

By

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ABSTRACT

RELATIONSHIPS BETWEEN CLIMATE AND CROP YIELDS
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Multiple regression models were developed for yields of selected field crops in Lenawee, Gratiot, and Gladwin Counties in Lower Michigan. Climatological data were obtained from National Weather Service cooperative observer records. Crops studied were corn, oats, soybeans, and dry beans in these counties where yield records were available for the specific crops.

Long-term trends were removed by calculating piecewise linear regressions for specific periods. Departures from trend were used as the dependent variable in multiple regression analyses. Predicted yield departures from the regression analyses were added to trend values to obtain predicted annual yields.

Two separate analyses were made. The first used monthly climate data for the April through September growing season for 1892-1977 in Lenawee and Gratiot Counties and 1926-1977 in Gladwin County. Independent variables were temperature; precipitation; soil moisture derived from soil water capacity, precipitation, and potential evapotranspiration; and the squares of each of these. The second

analysis used weekly temperatures and precipitation for the growing season of each specific crop.

For corn, soybeans, and dry beans, the most important climate factors were July and August precipitation. Temperatures in May and June were most important for oats. Use of a soil moisture availability index did little to improve the analysis.

Analyses based on weekly data explained a larger portion of the variation in yields (higher R^2) than those based on monthly data. A truncated mid- to late-season weekly model may be useful in developing early estimates of yields for the current crop year.

Removal of time trends from crop data prior to multiple regression analysis lowers R^2 values. However, this allows the analysis to deal with short-term variations which are largely influenced by growing season weather conditions.

ACKNOWLEDGMENTS

It is impossible to adequately thank or even mention the many people who have given of time, expertise, and concern in helping this research--and researcher--along. The major burden of counsel, advice and discussion was borne by Dr. Dale Linvill with grace, good humor, forebearance, and incredible patience. Committee members were Dr. Georg Borgstrom, Dr. Charles Cress, Dr. Jay Harman, and Dr. Fred Nurnberger. Their wisdom, insight, and effective suggestions are much appreciated. Mr. Don Fedewa of the Michigan Agricultural Statistics Service kindly consented to serve as outside examiner.

Fellow graduate students played an important role in providing suggestions, information, and moral support. Various faculty members in Agricultural Engineering but also in Crops and Soils and Agricultural Economics were valuable sources of information and counsel.

The involvement and sacrifices of my family over many years are the *sine qua non* for successful completion of the graduate study process. Most important of all has been the continued support of my wife, Elizabeth.

TABLE OF CONTENTS

Chapter | Page

LIST OF TABLES

LIST OF FIGURES

CHAPTER I

INTRODUCTION

This study seeks to contribute to our understanding of relationships between weather conditions in the growing season and variations in the yields of major field crops in Michigan.

OBJECTIVES OF THE STUDY

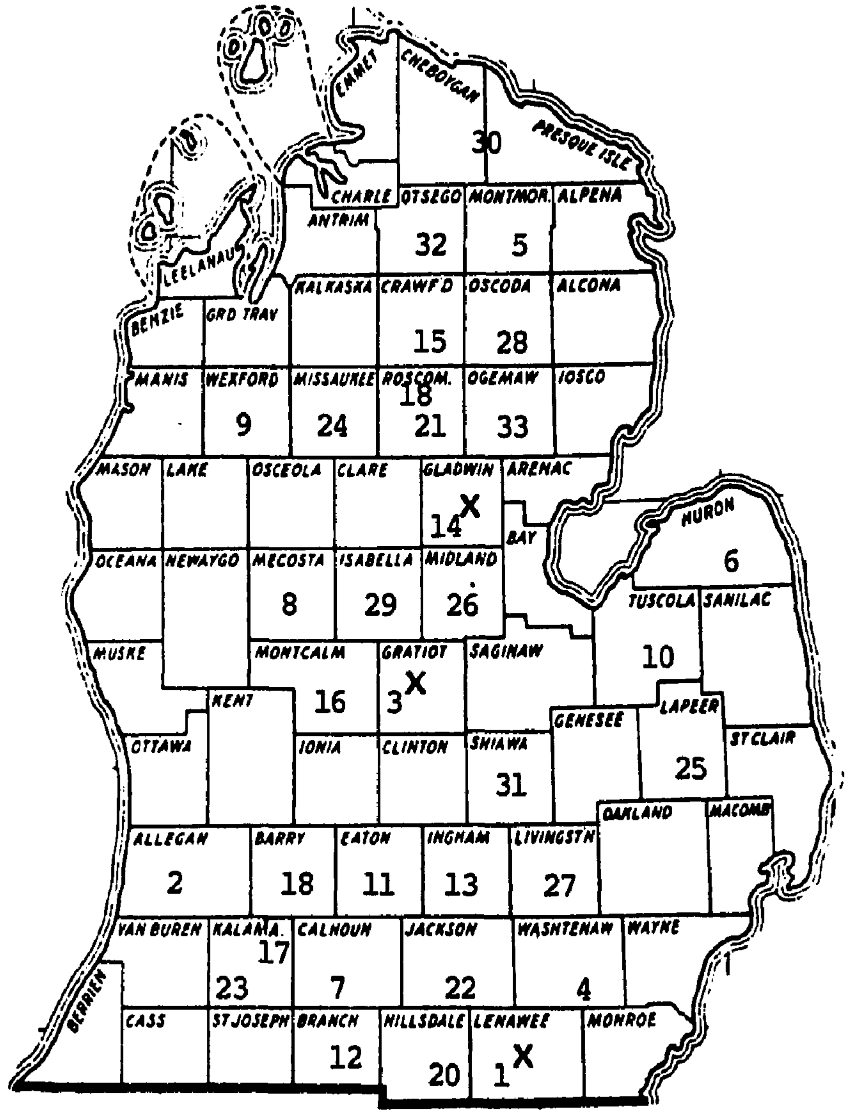
1. To determine long-term relationships between variations in climatic data available from volunteer cooperative observer records and variations in the annual farm yields of specific field crops in Michigan.

2. To determine at what times in the growing season weather variations are related to significant variations in crop yields.

3. To develop a predictive model for estimating annual county crop yields, based on local weather records for the current growing season, both at mid-season and at the end of the season.

SETTING AND PERIOD OF THE STUDY

Three counties in Lower Michigan, identified in Figure 1, were selected for this study. Lenawee County is located in southeastern Michigan, along the Ohio border. The weather observations for this study were recorded at Adrian, near the center of the county.



Numbers represent stations; see listing in Figure 2

xStations in the crop-yield study.

Figure 1. Location of Study Areas in Lower Michigan.

Gratiot County is located in central lower Michigan, lying partly in the Saginaw Valley with its former lake-bottom soils. The weather station used is located at Alma, near the center of the county.

Gladwin County is located just into the northern half of the lower peninsula, with marginal or near-marginal climatic conditions for warm-season crops. The observation station used is near the center of the county, in the town of Gladwin.

The period of the study includes 1892 through 1977 for Lenawee and Gratiot Counties. Climatic records began in Gladwin in 1926. Yield predictions are made for 1978 for all counties, based on climate data for that year.

RATIONALE FOR STATION AND CROP SELECTION

GEOGRAPHICAL CONTEXT OF CLIMATE STATIONS

An attempt was made to obtain records from stations along a south-to-north transect in Lower Michigan, as near the center or eastern center of the peninsula as possible in order to avoid "lake effects" from the nearby Great Lakes. As long a period of record as possible was desired, to provide a long-term data base and to allow maximum repetition of any existing patterns.

Inspection of mean growing season temperatures along a latitudinal transect up the peninsula reveals the presence of a climatic transition zone across the Saginaw Bay-Muskegon line in the center of the state (Figure 2). While it somewhat parallels the topographic rise to the higher elevation of northern Lower Michigan,

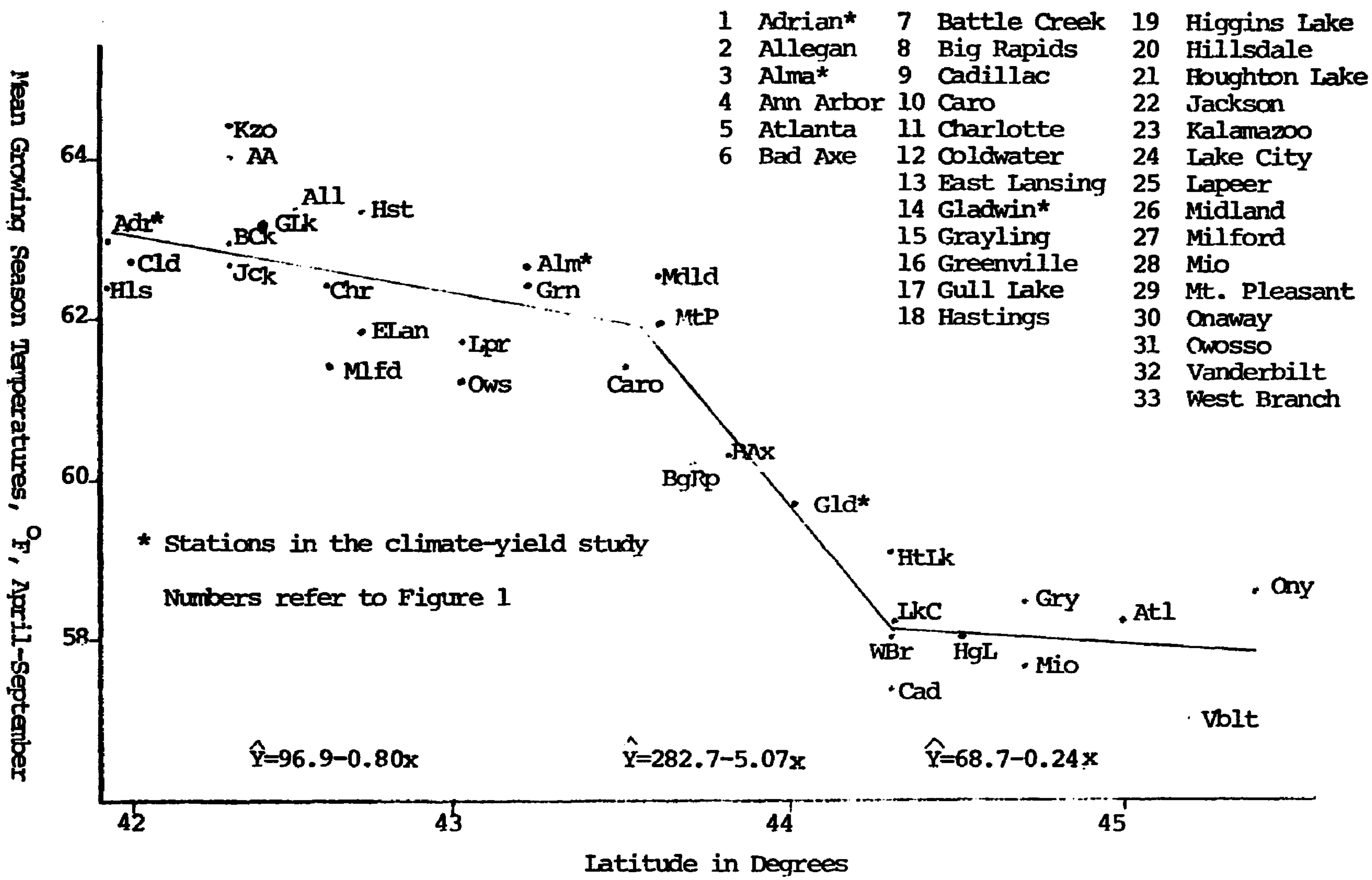


Figure 2. Mean Growing Season Temperatures vs. Latitude, Lower Michigan, Apr.-Sept.1940-69

it does not coincide with it. Gladwin and most of Gladwin County, despite being near the northern portion of the temperature transition, are at a relatively low elevation on the edge of the Saginaw lake plain. Both Adrian and Alma, south of the transition line, fall close to the trend line.

Inspection of climate records and on-site visits indicated that Adrian, Alma, and Gladwin best met the criteria for station selection. Other stations were deficient in length of record or relative historical microclimatic homogeneity; were in locations not representative of county agriculture; or were in counties with low crop acreages and thus insufficient crop records.

CROP DATA

Records of crop yields for the county containing the selected weather stations were obtained from publications of the Michigan Agricultural Reporting Service and its predecessors. Crops included were corn, soybeans, dry beans, and oats.

CORN

Recent archaeological studies have revealed that corn (Zea mays) was grown in northern Wisconsin until about 1200 A.D., when the northern limit for corn growing rapidly shifted to the present border with Illinois during a period of climatic deterioration. The cold, dry period, which drastically changed the Indian cultures, lasted about two hundred years (Bryson, 1975). Corn was found by early European explorers to be commonly cultivated by the native Indians in Michigan up to the shores of Lake Superior in the 16th and 17th centuries. Types grown in the cooler northern and drier western areas were short, hardy varieties (Weatherwax, 1923). Thus we may assume that corn production in Michigan antedates our archival records by a considerable margin, and that adapted genotypes were readily available.

Corn is exceeded only by dairy products as a source of cash farm income in Michigan, bringing in nearly $247 million in 1977, or two-and-a-half times as much as dry beans, the next greatest crop income source (Michigan Crop Statistics, 1979). Corn is a primary field crop common to many temperate areas. It has been widely studied and serves as a common denominator in climate-yield studies. Long-term records for corn are available for all three counties studied.

SOYBEANS

Soybeans are a relatively new crop in Michigan. They have been important enough to appear in the crop reporting records since 1942; thus data from Lenawee and Gratiot Counties are available from that time.

Soybeans respond to climate in a manner similar to corn. They are less common than corn in areas where climate or soil are marginal. They rank close behind dry beans in market statewide receipts, with $89 million in 1977 (Michigan Department of Agriculture, 1979).

DRY BEANS

Beans, like corn, were already being grown in America before the early Europeans arrived. Andersen and Robertson (1978) estimate that commercial dry bean production in Michigan started in the early 1880s. State records of bean production begin in 1895.

Dry beans are sensitive to climatic anomalies; in particular to excessive precipitation late in the growing season. They ranked second behind corn in Michigan cash farm income in 1977, with over $99 million (Michigan Department of Agriculture, 1979). Michigan ranks first in the nation in dry bean production, and provided 94.2% of the nation's navy beans in 1977 (Michigan Department of Agriculture, 1978). In the three counties selected, only Gratiot had dry bean acreage sufficient for study.

OATS

Oats are a cool-season crop, responding to climate in a manner different from corn or beans. While less important statewide as a source of cash receipts, they are important as a feed grain and as a rotation nurse crop for establishment of hay and grass seedings. Oat records are available since 1892 for all three counties in the study.

METHOD OF STUDY

In order to analyze short-term or year-to-year variations in yields, most of which may be ascribed to weather, long-term trends representing less than a single oscillation were removed. This was done by fitting linear regressions to segments of the yield data for each crop in each county, then using the annual deviations from these trend lines as the input data for analysis. Multiple regression analysis was applied for each case, with the above deviations as the dependent variables. Independent variables were temperature and precipitation for periods in the growing season. Separate analyses used monthly and weekly time periods. For the monthly analyses a moisture availability term was derived from a cumulative soil moisture budget, including precipitation and potential evapotranspiration, which was calculated by the Thornthwaite method. After calculation of predicted deviations from trend by the multiple regression models, annual trend values were added back in to provide predicted yields.

CHAPTER II

A REVIEW OF CLIMATE AND CROP MODELING

In a report discussing plans for a specialized National Agricultural Weather Service (Epstein, 1977) the present situation regarding crop-weather relationships is expressed as follows:

> Correlations between weather conditions and agricultural output have been made for certain crops at specific localities within the Nation, but, to date, no general information is available other than the fact that weather can be the most significant variable explaining year-to-year fluctuations in the yield of most commodities.

This chapter deals with research which has been done or is in progress with the objective of understanding, explaining, and predicting year-to-year changes in the yields of crops in this study.

VARIABILITY AND YIELDS

McQuigg (1975) gives three main sources of variability affecting the yield of grain crops over the years: (1) technological change; (2) meteorological variability; and (3) random "noise." He estimates that total variance about the sample mean is due 75 to 80% to technology, 12-18% to weather, and 5-10% to random noise. We note that at any given time the available technology is essentially at a given level. Thus the major year-to-year variant is the weather conditions that exist. In any case, McQuigg warns, the weather-technology interaction is still unresolved. We must be aware of the influence which this lack of resolution has on our model estimates.

Edey (1977) points out what has also been noted by several other authors: "It is increasingly evident that the greatest threat to food production is still the regional variability and fluctuation and not an overall long-term climatic change." These variations, especially in precipitation, often have a great impact on agricultural production.

Edey also noted three shortcomings in agroclimatic statistics. First, weather of the next 30 years will not necessarily be the same as that of the past 30. Second, "normal" weather does not exist; we can expect ranges and extremes which can sometimes be disastrous. Third, climatic records of a given station are not necessarily representative of a larger geographic area. Thus the impacts of spatial and temporal variability force us to go beyond normals and averages.

A WORLD VIEW OF CLIMATE AND CROP MODELING

Different climatic areas may have different limiting factors affecting crop production and yields. Crop-yield modeling activities in various parts of the world, as reported by Baier (1977a), tend to reflect local conditions. For example, statistical-empirical crop models in Iran and India stress water availability as a variable. In southern Brazil relative humidity in October is an important variable in estimating the yield effects of plant disease stress. Both temperature and precipitation are important variables in wheat models developed for the Anatolian Plateau in Turkey. In low-rainfall areas of Israel, annual precipitation figures correlate well with wheat yields. Distribution of rainfall as well as amount is important in India. In Australia a crop-water stress index is important in estimating water available in the root zone through the critical period for wheat.

Much of Canada is vulnerable to low temperatures. Baier (1977b), in his summary of the 1977 meeting of the Canada Committee on Agrometeorology, notes estimates that a decrease of 1 degree Celsius (1.8°F) in average summer temperature would decrease potential corn production in Ontario by about 30% and eliminate corn as a grain crop in most of the remainder of Canada. He concludes that the most probable change in climate is a trend toward more variability, both seasonal and yearly, in climatic factors which will affect agriculture.

McKay and Allsop (1977) state that climatic fluctuations, including brief climatic anomalies, are the major cause of variation in crop yields in Canada. In the prairie provinces, good years may actually be the anomalies. Planning must include an expectation of climatic variations.

RESEARCH IN THE UNITED STATES

Since this study is concerned with climate-crop yield relationships in Michigan, it will be most concerned with the portion of the nation which has relatively similar crop weather.

TRENDS IN MICHIGAN AND THE NATION

Wright (1976a) studied yield trends of specific crops in Michigan for the period 1950-1975, and compared Michigan yields with national trends for those crops. Both state and national yields showed a sharp increase for the post-World War II period. This was especially spectacular for corn, more than doubling the long-term Michigan average of 2016 kg/ha (32 bu/a), as shown by the above reference. Also shown is a lower rate of increase occurring in average yields, starting with winter wheat in 1964 and soybeans in 1968.

Dry beans in Michigan are a special case, with peak yields in 1964 and a downward trend since then. In contrast, national bean yields reached a plateau in 1961 and have remained high. While Michigan average yield decreased from 147 kg/ha (1310 lb/a) in 1960-64 to 121 kg/ha (1078 lb/a) in 1970-74, Ontario yields climbed from 133 kg/ha (1190 lb/a) to 156 kg/ha (1390 lb/a). For the latter period dry beans still followed corn and wheat in crop market value in Michigan (Wright, 1976b).

Clough (1968) quantified yield trends, applying 9-year moving averages to U.S. corn yields over the period 1916-1965. From 1916 to 1935 there was little change in yields. From 1935-1951 the average yield moved from 1640 to 2430 kg/ha (26 to 38 bu/a). From 1951 to the time of his study it had almost doubled, from 2450 to 4500 kg/ha (39 to 71.5 bu/a). He noted that variations in the percentage of average yield were smaller in the latter half of the period. He attributes this reduction to changes in production practices.

McQuigg (1976) found that the technological trend line of wheat yields in Oklahoma actually decreases since 1960. This includes not simply absolute yield, however, but also changing land-use practices, including release of land from government acreage reserves. Katz (1977) found that, although the 1960-1974 linear trend was negative, these data showed no significant (95% level) evidence that the slope of actual wheat yield was non-zero.

Experiment station soybean yields in Iowa, reflecting the state of the art, reached a relatively high level some years ago. Average farm yields are now approaching this level. However, station yields have not moved upward beyond that plateau, indicating that farm yields must also level off unless unforeseen new technological breakthroughs are achieved (Thompson, 1975).

TECHNOLOGY AND YIELD TRENDS

An examination of yield trends in recent years shows the effect of increased fertilizer use, higher-yielding varieties, higher plant populations, and other cultural practices. However, while this technology is still available, farm yields have leveled off and in some years dropped sharply. The years of increasing yields coincided with exceptionally stable and favorable weather which allowed us to carefully tune new practices to give optimum results under a narrow range of favorable weather conditions (Thompson, 1975).

Thompson (1969a) concludes that two factors account for most of the variation in wheat yields since 1945. Technology is assumed to be a major factor in the long-term increases in average yields, and weather is assumed to cause the variability around the long-term trend. Thompson (1969b) estimates that the two factors together explain from 85 to 90% of the yield variability.

Dale (1964) studied the effects of moisture stress on corn in experimental plots at Ames, Iowa from 1933 through 1962. He held fertility treatments as stable as possible, with most of the change in technology limited to higher-yielding varieties and higher plant populations. He concluded that, although technology is responsible for the steep upward trend during the latter part of the period, benefits from this technology were possible only because of the low level of moisture stress during that period. An adequately high number of "non-moisture stress days" are necessary to realize the effects of the improved technology.

RELATIONSHIPS BETWEEN CROP YIELDS AND CLIMATE

A major reason for concern regarding the weather is the inevitable impact weather has on food production. Considerable work is now being done on simulation modeling of crop yields, with climatic conditions as input variables. For such models to be valid, reliable information is needed for both micro-scale crop response and probable climatic conditions.

Thompson (1975) reviews the condition of complacency and over-confidence in high policy levels of the USDA generated by the unusually favorable and stable weather of the previous two decades. The official view existed that our technological expertise had reduced yield variations in both good and bad weather (Butz, n.d.). Thompson notes that the highly variable weather of 1974 shocked many people into a greater concern over the food supply. Resulting dislocation in grain markets, the livestock industry, international trade, and the economy as a whole caused serious financial losses as well as boosting inflation.

While anyone who has been close to the land has an intuitive understanding that yields are closely related to growing-season weather, intuition is an insufficient basis for scientific analysis. We will look first at techniques which have been useful in studying these relationships, then at some results obtained from recent research.

SOME TECHNIQUES USED IN STUDYING CROP-CLIMATE RELATIONSHIPS

Most crop-climate studies are of two types, or a combination of these: (1) Simulation studies or physiological models; these attempt to mathematically model the growth process in a given season. (2) Climate-crop yield or empirical-statistical models; these estimate yield on the basis of statistical relationships from a series of yield and weather data. We are concerned primarily with the second type of study. While this second approach draws on a large amount of data and shows what happened before, it does not necessarily show cause and effect. Spurious relationships may occur which have no physical basis in biological reality.

Nelson and Dale (1977) state that year-to-year changes in yield over a short period of years should be predicted mostly in weather terms in a multiple regression model, rather than by technological terms. They also note that predictions of the effects of technology on yield depend quite a bit on just what time-weather series is used. This can introduce large errors in yield predictions. They ascribe the larger errors in the 1970s to more highly variable weather.

Katz (1977), in a sensitivity analysis of statistical crop-weather models by the use of ridge regression techniques, found that a lack of reliability was inherent in coefficients estimated by multiple regression. Sources of errors were: (1) relationships between crop yields and a given climatic variable were non-linear; and (2) climatic variables which were used as predictors possessed some amount of correlation between them. He states that the multiple regression models in question have been valuable in showing the definite effect of weather variability on yields, but warns that we must be aware of their limitations.

Haigh (1977) developed structural models to separate year-to-year variability of crop yields into the effects of weather and those of management, using coefficient of variation analysis for the period 1935-1970. He asked two questions: (1) Has better management reduced the effects of bad weather on crop yields; and (2) Has the upward trend in yields leveled off in recent years?

His analysis showed that the percent of yield variation explained by management over the period 1928 through 1976 is about two to three times that explained by weather. The interaction of the two accounted for 10 to 20% of the variation in yield. This analysis could be of added value if it were repeated, based on 1965-1976 technology, rather than on the 1940-1970 period of rapid technological improvement.

Haigh concluded that: (1) there was no evidence found that technology has reduced the sensitivity of grain yields to weather; (2) there is no statistical evidence that increases in grain and soybean yields were leveling off by 1970.

RESULTS OF CROP-CLIMATE STUDIES

CORN

Robbins and Domingo (1953) tested the effect of soil moisture depletion to the wilting point at different stages of development. If moisture were removed before tasseling, low yields resulted. Depletion four weeks after tasseling caused significant reduction in yield, but depletion seven weeks after tasseling appeared to cause no significant difference. They concluded that soil moisture was critical only until the corn reached maturity. Following maturity, soil moisture depletion did not affect yield or moisture content. Yield reductions were therefore related not to total amount of water available but to the duration and timing of moisture deficits.

Denmead and Shaw (1960) also studied the effects of soil moisture stress at different stages of growth on the yield and development of corn. They found that effects on yield of stress at the vegetative stage amounted to about 25%; during silking, about 50%; and at the ear stage, 21%. They further determined that as stress periods recurred, total effect seemed to be less detrimental, as the earlier stresses apparently hardened the plant.

Dale (1964, 1965, 1968) showed that rapid increase in Iowa corn yields, usually credited to improved technology and cultural practices (especially higher plant populations), was possible only due to very favorable weather enjoyed in Iowa for the preceding three years, as well as the 1948-1965 period.

Thompson (1969b) used a multiple curvilinear regression on corn yields in the Corn Belt from 1930 through 1967 to determine the influence of weather. In order to remove the effect of technology, he used one linear trend line for the period 1930-1960 and a second for 1960-67. The main factor affecting yields was July rainfall. Following, with a combined effect less than July rainfall, were (1) the occurrence of average precipitation from September through June; (2) normal June temperature; (3) above-average rainfall in August; and (4) temperature slightly cooler than usual in July and August.

Holt and Timmons (1968) found in South Dakota and Minnesota that, as precipitation increased, higher stands, up to a maximum of 54,400 plants per acre, gave higher corn yields. Precipitation during late July and early August, as the corn approached silking, affected corn yield more than that received during early July.

Lawlor and Liebhardt (1978) developed a climatic model using a daily water budget. Preliminary results from Maryland showed that a July and August moisture deficit is related to lower yields, while a surplus in June shows a positive correlation.

Runge and Odell (1958) found, through a multiple correlation study of experimental plots at Urbana, Illinois for 1903 through 1956, that corn yields were influenced most strongly by precipitation preceding anthesis (beginning of pollination) and by maximum temperature during anthesis. They found that a phenological approach using date of anthesis explained more of the yield variability (67%) than one based on fixed calendar dates with 8-day periods (58%). Including trend by year increased the amount of variation explained by temperatures and rainfall to 75%.

Schaal and Blair (1968) found that in corn production in Tippecanoe County, Indiana, the best corn yields occurred in years when temperature averaged above normal during the establishment period and below normal during the grand growth and reproduction periods.

Runge (1968) found that high maximum temperatures of 90 to 100 degrees F (32-38°C) can be beneficial to corn yield if the plant has adequate available water. He found that maximum temperature and rainfall have a large effect on yield from 25 days before to 15 days after anthesis. At Urbana, this period occurs on the average between June 30 and August 8. Maximum yield effect occurs at approximately one week before anthesis. Actual effect on yield depends on the specific combination of temperatures and precipitation which occurs. This interrelationship could be expected to occur due to the effect of temperature and available moisture on transpiration.

This brings up an important source of error in the interpretation of statistical studies. A comparison of corn yield with temperatures suggests that higher-than-normal temperatures are related to decreased yields. Runge's study suggested, however, that the cause of decreased yield under high temperatures is not due to the high temperatures themselves, but rather (1) drier conditions associated with clear, rainless skies, and therefore more insolational heating; and (2) increased moisture stress due to increased evapotranspiration at higher temperatures and levels of radiation. If adequate water is available, higher temperatures may in fact increase rather than decrease yield. Thus interaction between temperature and precipitation variables may exist at high temperatures, but not be reflected in the model developed from long-term data. Runge's statement may be relevant in not only whether or not to irrigate, but also in selecting methods of irrigation.

Runge and Benci (1975) used average weekly maximum temperature and total weekly precipitation data as the growing season progressed, as well as certain soil factors, to project corn yields for that season. They concluded that with present technology, man-induced or natural climatic change or variation would have a considerable influence on corn belt production.

Dale and others (Dale and Hodges, 1975; Dale, 1977a, b) developed an Energy-Crop Growth (ECG) variable as part of a crop growth simulation model. This was later adapted for use in a climate-yield prediction model for the Tippecanoe County corn yield study for the period 1957-1975. It includes radiation, a leaf area index (Linvill, 1972), and a ratio of actual to potential evapotranspiration, but excludes a temperature factor. Combined with a nitrogen use index, it explained 67% of the variance in county-corn yields. Nitrogen was used as a proxy variable for improvement in technology over time. This appeared to be an improved method of handling the time trend and/or technology component which is a problem in the Thompson-type multiple regression approach.

Dale points out the interaction between weather and management which is represented by the N variable. Higher levels of N are related to high yield response when the weather is favorable. During seasons with unfavorable weather, higher levels of N do not produce higher yields. He states that the yield response to one depends on the level of the other.

Achutini, Eddy, and LeDuc (1979) studied corn yields in Iowa and Illinois for the period 1928 to 1973 using a simple multiple regression model. For the years 1949-1973 they concluded that corn yields in these two states were largely a function of technology, with nitrogen fertilizer accounting for most of the variation. However, they point out that technology cannot compensate for yield reductions due to weather variability. They also tested models which were truncated after the planting [sic] and silking stages, with some loss of accuracy.

A study of the effects of precipitation alteration in Kansas (Bark, 1978) included statistical crop yield prediction models. This study used the Thompson approach, including a linear time trend assumed to represent technological improvements over the period of the study. The variables for the corn model in the eastern one-third of Kansas included monthly temperatures for May through August, plus October, and squared terms for each of the above. Palmer "d" values, which include both precipitation and stored soil moisture, were tested as variables to replace monthly precipitation. However, results were inconsistent, so precipitation was used. Also included in the equation was a technological time trend constant C(1) = 1.443 for the years 1946-1975, used as C(1) x (year-1899). The use of all 11 terms plus the trend constant and the regression constant in the equation gave an $R^2 = 0.91$ and a standard error [sic] of 6.71 bushels per acre.

Nelson and Dale (1978) used analysis of variance to evaluate the accuracy of four statistical models applied to selected Indiana counties. The traditional multi-variable linear or "Thompson" model used twelve weather and three technology variables. Weather variables were June, July, and August mean temperatures and precipitation, their squares, and pre-season precipitation from September to June. Technology variables were a linear time trend which was incremented by one year from 1941 through 1960, and constant thereafter; a linear term incremented by one each year after an initial value of 1 in 1960; and the square of the latter. The modified Thompson model used the same weather variables but replaced the three technology variables with a single variable representing average annual nitrogen use on corn land in Indiana.

The third model was the 14-term Leeper model (Leeper, Runge and Walker, 1974), using experimental-plot technology adjusted for estimated average state level of technology use. Weather variables were represented for 6 weeks before to 4 weeks after average tasselling date. The 14 terms included linear and quadratic terms for available soil water at planting time, plus 12 complex summation terms. The summation terms were based on weekly precipitation and mean daily maximum temperatures. The individual terms and their cross products were weighted by linear and quadratic week numbers 1 to 10. Where appropriate these summation terms were also multiplied by the amount of available stored soil water at planting time.

The fourth model replaced all weather variables with a single Energy-Crop Growth (ECG) index. This was a summation of 84 daily ECG values, from 6 weeks before to 6 weeks after 50% silking. Daily ECG values were based on solar radiation, a leaf area index, and on actual and potential evapotranspiration. Where radiation data are not available, ECG may be approximated by using ET. The regression model is composed of the ECG index, nitrogen used for corn, and the interaction of the two.

Both the Thompson and modified Thompson models were regressed with full (all variables) and stepwise (critical F value of 2.0) versions. Years tested were 1971 through 1975. Errors of prediction in any single year varied from 4 bu/a in the Leeper and ECG models to 37 bu/a in a full Thompson model with 3 technology variables. Lowest yearly average error for the 5 years was 9 bu/a in both the full and modified Thompson models with nitrogen use as the technology variable. Without the anomalous 1974 figures, lowest average error was 7 bu/a for the same two models.

The ECG-ET model, Leeper's 14-term model, and the Thompson model with nitrogen use substituted for technology trend variables gave approximately equal levels of prediction accuracy, within about 10 bu/a. The Thompson model with three technology trend variables proved to be less accurate.

Huda and Runge (1978) developed and tested ten corn yield models for universality, and also tested two other models. They found that the 14-term model developed by Leeper was the best predictor for ex ante estimation of corn yield.

Niell and Huff (1979) used a technological index plus monthly temperature and precipitation in a crop-weather regression model for 1931-1975 in the midwest corn belt. A quadratic term for the technological index plus July precipitation and temperature and the August temperature were the significant variables. Various combinations of pre-season precipitation and interaction terms between the climatic variables were input but were not selected by the regression process. The same basic equation with the same variables was applicable to all 45 crop reporting districts in Illinois, Iowa, Indiana, Missouri, and Ohio.

SOYBEANS

Much less attention has been given to soybeans than to corn. Gross and Rust (1972) found by multiple regression methods that, for the period 1956-1965 in Minnesota, the climatic variables most highly correlated with yield were May, June, and July temperatures and the state of soil moisture on the first day of June, July, and August.

Non-climatic variables were applied nitrogen, phosphorus, and potash, plant population, and planting date.

The soybean model by Bark (1978) used a time trend plus precipitation for July through October and temperature for May through August, plus October. R^2 for this model was 0.92, with a standard error [sic] of 2.05 bu/a.

Runge and Odell (1960) found that, for Illinois experiment station yields from 1909 through 1957, 68% of the variation lay in precipitation and the maximum daily temperatures. Greater than average rainfall before July 1 decreased yields, but after that date it was beneficial. Yields were reduced by hard rains and cloudiness during the first half of August. Above-average rainfall before June 25 and after September 20 helped, but were detrimental between these dates.

Thompson (1962, 193, 1970) studied soybean yields in the Corn Belt for various periods from 1930 through 1968 by multiple regression analysis. He found that the two most important weather variables were above-average July rainfall and below-average August temperatures. August precipitation was relatively more important for soybeans than for corn, as their shallower root systems are less able to tap deeper subsoil moisture. He concluded that, while technical inputs to production helped increase yields from 1935 to 1961, a major part of the increase in production was due to the unusually favorable weather in the latter half of the period.

Niell and Huff (1979) studied frequency distribution of weather-related deviations from technology trends in corn and soybean yields for 1931-1975. Monthly weather data were used. Below-normal yields were primarily related to moisture deficits, but also occasionally to excessive precipitation. Above-normal yields tend to occur with normal or above-normal precipitation combined with normal or below-normal temperatures in July and August. They also found that negative deviations in yield were consistently larger than positive deviations. They also found that soil characteristics, apparently water-holding capacity, were more strongly related to crop weather sensitivity than were spatial differences of climate.

In seasonal soybean-weather simulation model, Ravelo and Decker (1979) found that for the central United States, weather from the flowering stage to maturity has the most influence on yield prediction.

Hill, Johnson, and Ryan (1979) also used seasonal simulation of soybeans during four growth stages from flowering to maturity. The most moisture-critical period was during the pod-filling stage.

DRY BEANS

It appears that, despite their susceptibility to direct yield effects and climate-induced disease problems, the question of climate-yield relationships in dry beans has not been adequately addressed. A computer search of 8000 biological publications for the period 1970-1978 (BIOSIS) yielded no relevant articles on the subject.

Earlier, Robbins and Domingo (1956) found yield reductions of about 20% on dry beans in coarse-textured soils in the Columbia Basin under certain moisture-stress conditions. This occurred when visible moisture stress persisted for 15 days prior to blooming; 18 to 22 days during blooming; and about 15 days before the first pods ripened. Stress late in the season hastened ripening of the crop, but bean weight was reduced due to failure to reach maturity. Moisture deficits before blooming retarded development of the plants. Irrigation before the plant showed visible moisture stress at any time in the season appeared to have no advantage.

Smucker, Mokma, and Linvill (1978) note that dry bean plants are very susceptible to oxygen deficiency due to flooding. Flooding for more than 24 hours at the preflowering stage reduced yield by 50%, and by 25% when flooded during flowering.

OATS

Oats also appear to have received little attention in terms of yield response to weather. If the present cooling trend continues, they may emerge as a much more important crop in northern areas on the fringe of the Corn Belt, since they grow well in temperatures cooler than those required for corn, soybeans, and dry beans. However, the computer search noted earlier yielded only two references, both of which dealt with yield studies in Florida.

Pfahler (1972) found, in a study of 94 oat populations in Florida over a six-year period, a "negative relationship" between yield and environmental variability. Selecting varieties for high yield generally resulted in populations with low environmental variability.

McCloud (1977) studied yield trends and variability for eight major Florida field crops. He assumed that the long-term trend was due to technology, and that variability from this trend line was due to weather. Oats and corn showed increased yield variability at higher yield levels. He noted that most of the eight crops studied, including corn, soybeans, and oats, had apparently reached a yield plateau.

SUMMARY

Awareness of the role of climate in the problem of feeding the world's people is gradually growing. Recent weather-triggered crop disasters have shaken some of the complacency which resulted from technological developments concurrent with an exceptionally long run of favorable weather.

The USSR and Canada, due to their vulnerability to cold seasons and cooling trends as well as moisture deficiency, have become very active in biometeorological research. Canadian scientists have concluded that climate variability is more threatening than a cooling trend, and that increased variability is probable in the years ahead (Baier, 1977b).

Crop yields in the United States and in Michigan have passed through a period of dramatic increase, but have since leveled off. Until recently, this increase was ascribed to technology; now it appears that at least part of this increase was due to a period of relatively favorable weather. This period of favorable weather may now be over. A problem still exists in separating out technological effects on yield from climatic effects.

Most widely-used techniques for evaluating crop-climate relationships are statistical multiple-regression models. While they may have limited accuracy, they are useful for determining the nature of relationships.

One approach is to use time as a proxy variable, assuming that the long-term trend reflects improvement in technology and management. Shorter-term variations around the trend are considered to be due to weather effects. This does, however, fail to clarify either long-term weather trends or shorter-term variations in management.

The critical stress period for corn appears to be during tasselling and silking. Yields are affected most by lack of moisture in late July and early August. Soybeans are favored by above-average rainfall in July. Information was inadequate to provide conclusions in regard to dry beans and oats.

A factor repeatedly stressed is that high yields in the 1960s are partially due to an unusually long run of favorable, stable weather. The slowing in the rate of increase in yields with the more variable weather of the 1970s gives ex poste support to this view. We note that most studies and climate-yield models continue the steep upward trend line prevailing over most of the past 20 to 40 years. Recent crop yield trends show that this is not the actual case.

CHAPTER III

CLIMATE AND CROP DATA: SELECTION, PREPARATION AND ANALYSIS

SELECTION OF STUDY AREA VIA CLIMATE RECORDS

Data for this study were obtained from long-term National Weather Service records taken by volunteer observers. In order to observe the transition from corn belt to marginal climate and soil conditions, a lengthwise south-to-north transect of the lower peninsula was taken. Station sites were restricted to near the center or eastern center of the peninsula in order to minimize lake effects from Lakes Huron, St. Clair, Erie, and especially Lake Michigan. Such "lake effects" may have an influence of several degrees on temperature for many miles inland from the eastern shore of Lake Michigan. Minimum and maximum temperatures are also affected, as are growing season lengths. Cloudiness and precipitation may be affected less sharply, but for equal or greater distances inland (Seeley, 1917). A long period of record was desired, in order to provide a data base as large as possible and to show maximum repetition of any potentially existing patterns. Spatial distribution was also considered.

Within these constraints stations were chosen for the best quality of records available. This required a minimum of serious gaps in the record, and no known problems of consistency and reliability. The station should be stable with a limited number and distance of moves, either horizontal or vertical. Any moves should not involve extensive microclimatic changes. Station sites should possess no climatic aberrations atypical of the county crop areas. Present sites were visited and past locations traced, to assure that records would not contain excessive variations due to site changes or causes other than actual climatic variation.

Another consideration in selection was whether or not the station records have been computerized and processed by the Michigan Department of Agriculture/Michigan Weather Service. This increased the availability and accuracy of the data for a station, and also supplied additional processed data for analysis. Such criteria resulted in the elimination of all but Adrian in Lenawee County, Alma in Gratiot County, and Gladwin in Gladwin County. Each of the three had undergone some relocation during the period of record used, but present and past sites were judged to be reasonably similar in microclimate.

MONTHLY CLIMATE DATA

ESTIMATION OF MISSING DATA

Despite the selection of stations with the best possible records, there were times over the years when observations were simply not taken. Adrian data were nonexistent for January through June of 1903, April of 1908, and April through November of 1928. Gladwin data were missing for October-December 1927, March-August and October-December 1928, August 1939, and January-May 1941; and incomplete for May and December 1976 and April and October 1977.

TEMPERATURE

In order to estimate missing temperature data, stations with fairly complete records within a 40-mile radius were used. For Adrian, this included Ann Arbor and Hillsdale, and for Gladwin stations at Mt. Pleasant, Midland, and West Branch were used. Gladwin and adjacent stations showed more variations in records than Adrian due to greater differences in topographic and micro-climatic environments.

Linear regressions were calculated between each of the check stations (x's) and the subject station (y) for periods which included, when possible, at least 12 months before and 12 months after the missing data. When feasible, specific missing months of the year were also replaced with the nearest same months beyond the above 24 months in order to maintain the annual balance of monthly temperature levels.

Discrepancies between Hillsdale-based and Ann Arbor-based estimates for a missing month at Adrian ranged from .01 to 2.25°F (.005 to 1.25°C). All but two of the 16 estimates showed less than 1°F difference from the two sources.

Largest discrepancies between Gladwin monthly temperature estimates based on regressions against Mt. Pleasant, Midland, and West Branch ranged from 0.28 to 6.64°F (0.15 to 3.7°C). The latter was due to a very low average at Mt. Pleasant for April 1928.

Second largest discrepancy was 3.60°F (2.0°C). Of the 19 other estimates, 6 had differences of less than 1°F (0.55°C), 6 were 1 to 1.99°F (0.55 to 1.1°C), and 7 were 2 to 2.99°F (1.1 to 1.7°C).

Adrian temperature estimates were judged to be reliable within 1°F (0.55°C) and Gladwin estimates within 3°F (1.65°C).

PRECIPITATION

The linear regression technique was tested on precipitation data. Due to relatively large variations in precipitation totals between stations from one month to the next, this method proved to be inaccurate.

Isopleth analysis proved to be a more accurate method of providing missing monthly precipitation data than the use of linear regressions. Rather than depending on widely fluctuating relationships between stations for a period of months, the isopleth analysis considered the areal distribution of precipitation for each single month in question.

Monthly precipitation totals for all available stations in the Lower Peninsula for each specific month which had data missing were posted on a state map at the station location. Isopleths of equal precipitation (isohyets) were sketched at one-inch rainfall intervals. The missing monthly precipitation for the subject station was estimated from the isohyets and nearby stations. Estimates were judged to be reliable to within one-half inch.

The above processes provided data for the years 1892-1977 for Adrian and Alma and 1926-1977 for Gladwin.

TRANSFORMATION OF MONTHLY DATA

Two new groups of variables were derived from the initial observer data. These were (1) non-excess precipitation, and (2) a moisture availability index.

NON-EXCESS PRECIPITATION

Much of the growing season precipitation occurs in convective storms. Thus the precipitation record and unadjusted soil measure budget may include precipitation which has become unavailable for plant growth due to surface run-off of the excess. To determine the effect of this, two versions of non-excess precipitation were calculated, with precipitation in excess of one and two inches in any calendar day removed.

As an indication of the frequency of excess rainfall occurrences, probabilities of one calendar day with over one and over two inches of rainfall within a given growing season month are shown for each growing season month in Table 1. This probability was determined by dividing the number of days in which excess rainfall occurred within that month during the record period by the number of times the month had occurred (i.e., number of years). These figures are based on the years of 1917-1977 for Lenawee and Gratiot Counties and 1926-1977 for Gladwin County.

A MOISTURE STRESS INDEX

A cumulative soil moisture budget or "bank balance" approach was used to estimate the amount of water available for crops during the growing season on a monthly basis. The basic relationship is:

Table 1. Probability of One Day per Month with Excess Rainfall

	Adrian, 1914-1977		Alma, 1914-1977		Gladwin, 1926-1977	
Month	over 1"	over 2"	over 1"	over 2"	over 1"	over 2"
April	.453	.031	.219	.016	.414	.019
May	.625	.109	.641	.047	.481	.019
June	.719	.063	.672	.031	.654	.096
July	.813	.125	.500	.094	.673	.096
August	.625	.063	.750	.156	.636	.115
September	.672	.063	.735	.078	.636	.058

Table 2. Day Length Indices for Adrian, Alma, and Gladwin

Station	April	May	June	July	August	September
Adrian	1.074	1.190	1.236	1.235	1.138	1.014
Alma	1.078	1.199	1.243	1.240	1.201	1.014
Gladwin	1.083	1.207	1.250	1.246	1.210	1.014

$$MSI(m) = MSI(m-1) + P(m) - PET(m)$$

where

MSI = Moisture Stress Index

m = a given month

P = monthly precipitation in cm

PET = potential evapotranspiration in cm

The budget is calculated for the growing season, April through September. For the initial month of April, MSI is calculated by:

$$MSI(Apr) = NSC + P(Apr) - PET(Apr)$$

NSC is the net soil capacity, or water available for plant growth.

NET SOIL CAPACITY (NSC)

The soil profile in Michigan is assumed to be at field capacity (FC) at the start of the growing season. It is also assumed that the plant can continue to extract water from the soil until the permanent wilting point (PWP) is reached. Thus NSC = FC - PWP.

To obtain the value of NSC, soil types used as cropland in the county were determined from Soil Conservation Service county surveys. Percent of each soil type was listed; soil water capacities for each type were determined; and a quantity-weighted average of net soil water capacity was obtained. This calculated average NSC was

0.18 inches of water per inch of soil, ±0.04 inch, or 2.16 inches 5.49 cm) of water for the one-foot (32 cm) depth for all counties in the study. This quantity was used as a relative, rather than absolute, term; root depth and depth of drying were not used in the analysis.

POTENTIAL EVAPOTRANSPIRATION (PET)

The PET term in the Moisture Stress Index was computed by the Thornthwaite method. Historical climate data included temperatures but did not include relative humidity, wind, or radiation, which are required by other methods.

The Thornthwaite method is not accurate over short periods, or for spring only or fall only measurements (Rosenberg, 1974). It does work well over the span of the entire growing season in the temperate, continental climate of the eastern and midwestern United States where there is a strong correlation between temperature and radiation (Chang, 1968).

The Thornthwaite equation is expressed as follows, with terms defined below:

$$PET = DLI \times 1.6 \times (10T/I)^{a}$$

"DLI". A day length index specific for the latitude of the station. It is based on sun path diagrams for 40 and 45 degrees N. latitude (Brown, 1973), interpolated for the latitudes of the observation stations and corrected for day length on the 15th of each month. Day length indices for the months of April through September are shown in Table 2.

"T". This is mean monthly temperature for each growing season month each year, in degrees Celcius.

"I". "I" is an annual heat index which is constant for a given location. It is the sum of 12 monthly heat indices, "i", where i is a function of monthly normal or long-term mean temperatures. For temperatures below 0°C, i is assumed to be zero. The value of i is computed by $i = (t/5)^{1.514}$ where "t" is the mean monthly temperature. Palmer and Havens (1958) have provided a table by which values of "i" may be obtained from monthly normal or average temperatures.

"a". The exponent "a" in the Thornthwaite equation is constant for a given location. It is calculated from I by:

$$a = 6.75 \times 10^{-7} I^3 - 7.7 \times 10^{-5} I^2 + 1.792 \times 10^{-2} I + 0.49239$$

MOISTURE AVAILABILITY INDEX

The Moisture Stress Index was transformed into a Moisture Availability Index. The lowest value of the MSI was -32.97. Therefore the constant value of 34 was added to all MSI values to obtain positive MAI values. For versions of the regression analysis involving non-excess precipitation, MAI was calculated with the precipitation term replaced by non-excess precipitation.

ANALYSIS OF MONTHLY CLIMATE DATA

TEMPERATURE

Much has been said in recent years about large-scale climatic cooling trends. If a systematic downward trend in temperatures exists it would have implications for the range and development of agricultural crops, particularly along the climatic margins.

Decadal means of mean annual temperatures suggest a cooling trend (Figure 3). However, the temperatures during the growing season would be more important in terms of possible effect on crops. Figure 4 shows mean temperature for the April-September growing season over the period of this study. Inspection of Lenawee County temperatures indicates a downward trend over the approximately last 40 years. Gratiot and Gladwin temperatures do not show any apparent trend.

PRECIPITATION

Precipitation for the growing season for Adrian, Alma, and Gladwin is shown in Figure 5. Inspection does not reveal clear patterns over time for any station.

WEEKLY CLIMATE DATA

The majority of the Thompson-type statistical crop-weather models reported in the literature use monthly climatic data. Climate data on a monthly scale, while more widely available, tend to dilute the discernable impacts of weather events and conditions on critical stages of plant growth.

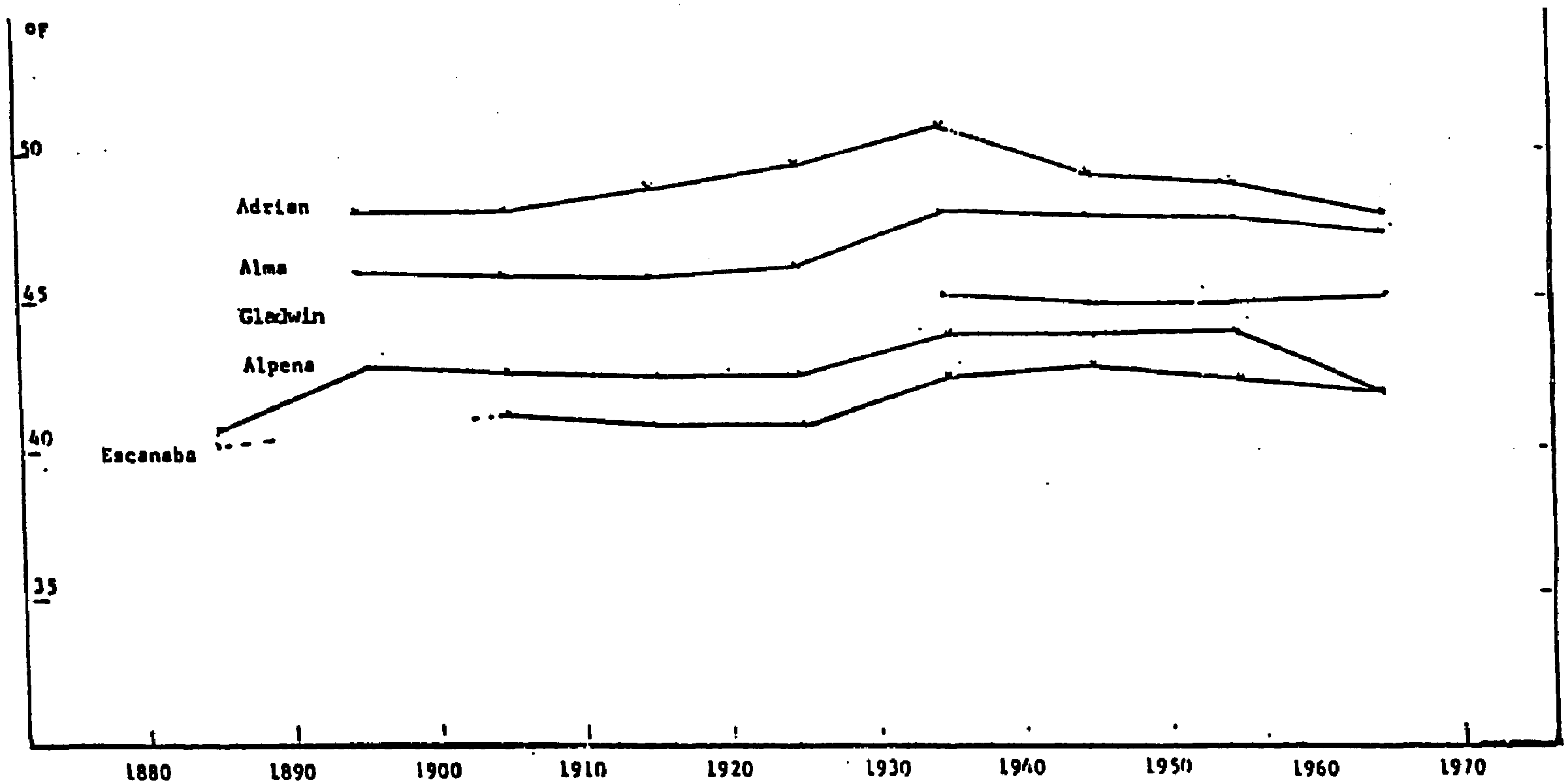


Figure 3. Decadal Means of Mean Annual Temperatures, Selected Michigan Stations, 1880-1969

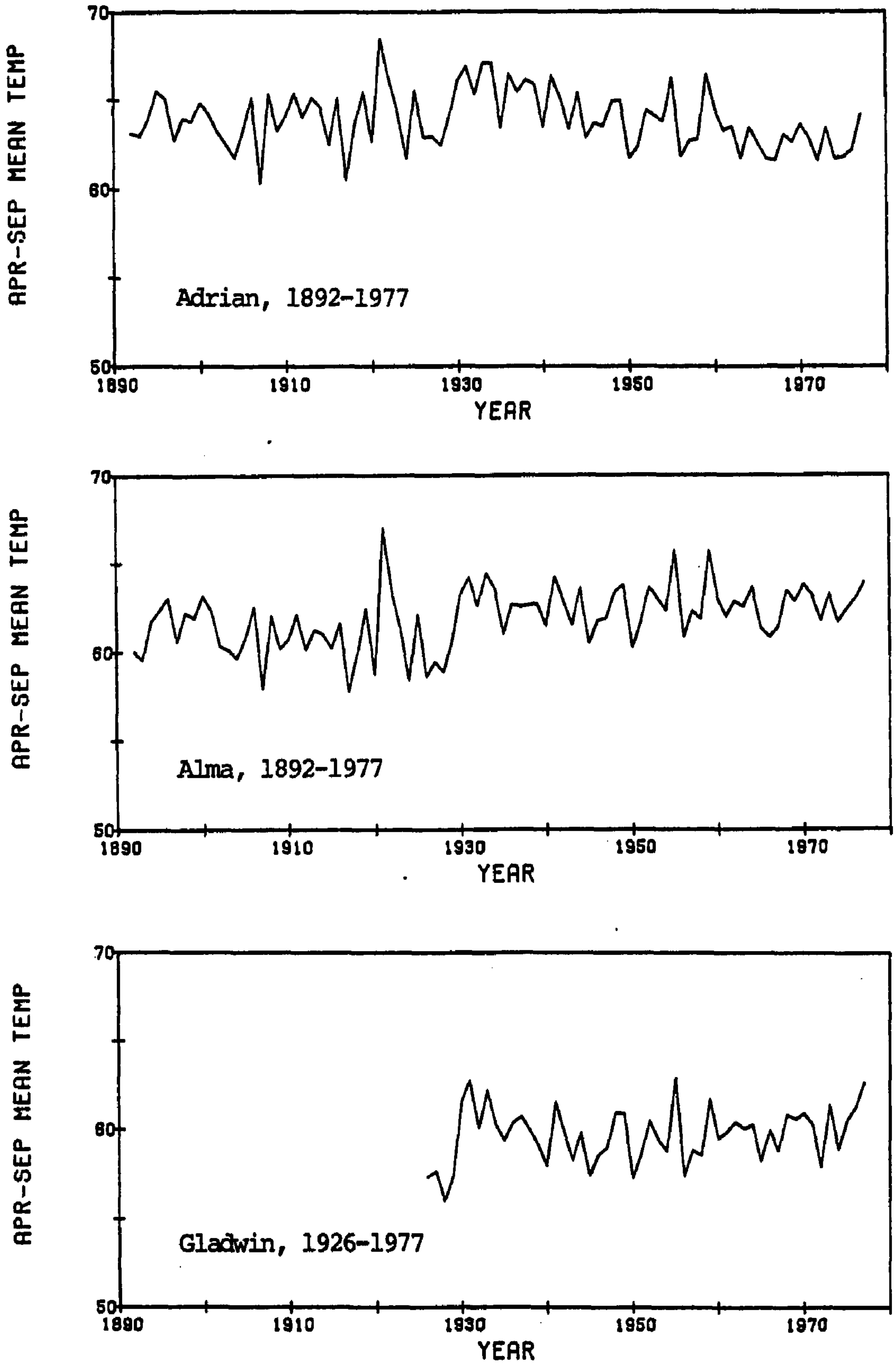


Figure 4. Mean Growing Season Temperatures by Year.

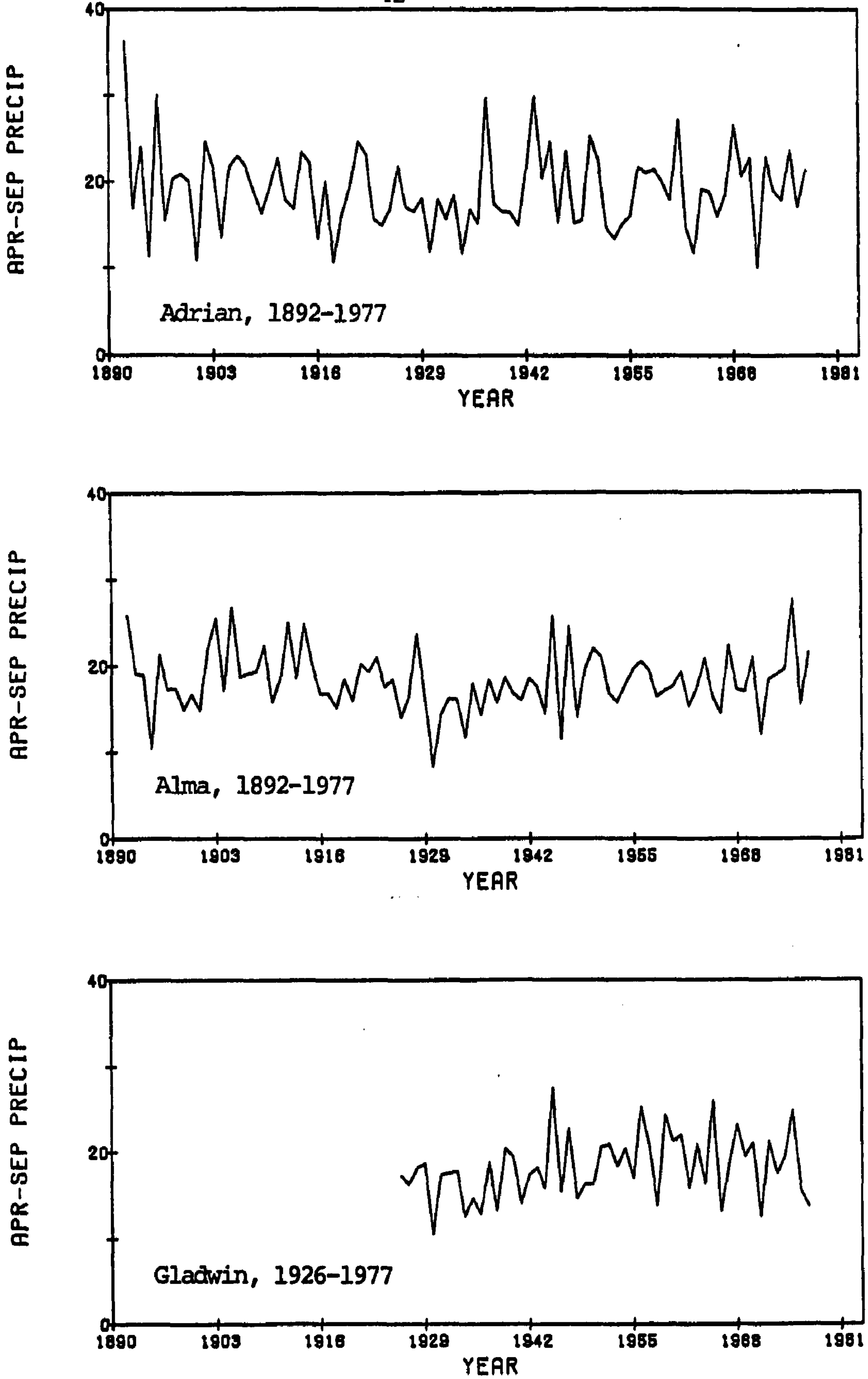


Figure 5. Growing Season Precipitation by Year.

When weekly summary climate data became available for Lenawee and Gratiot Counties, a regression analysis was developed based upon weekly temperature and precipitation. For data purposes the week beginning March 1 was designated as week 1. Growing season data end on October 31 at the end of week 35. For ending dates of numbered weeks the reader is referred to Table 10. This part of the analysis based on weekly climate data covers the years from 1943 through 1977.

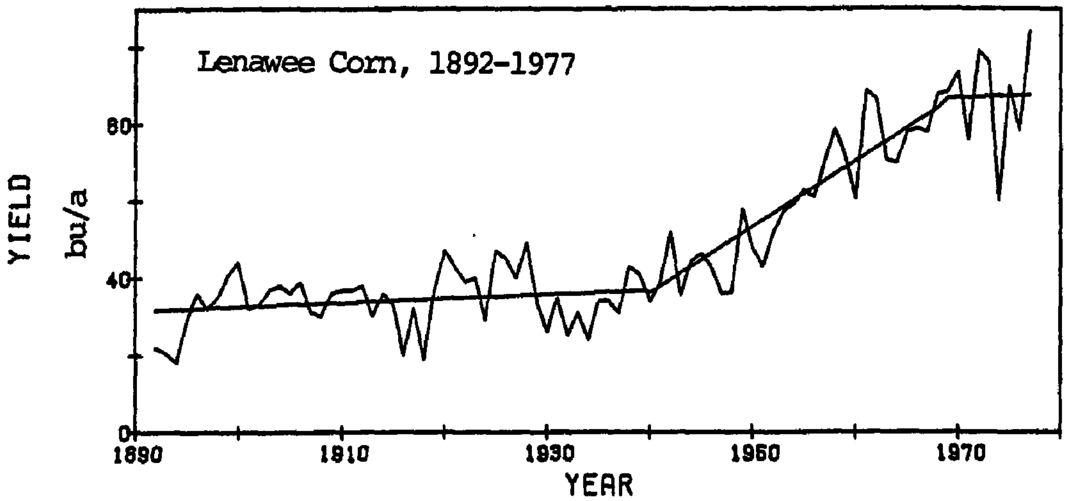
CROP DATA

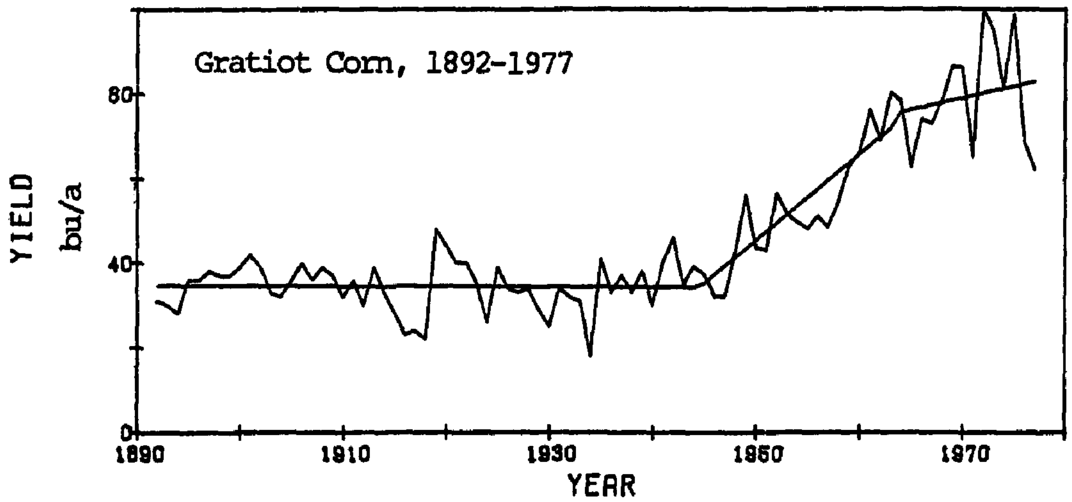
SELECTION

Crops selected for study were corn, oats, soybeans, and dry beans. For the monthly analysis corn and oats are studied for 1892-1977 in Lenawee and Gratiot Counties and 1926-1977 in Gladwin County; soybeans for 1942-1977 in Lenawee and Gratiot Counties; and dry beans for 1895-1977 in Gratiot County. These limitations were caused by the period of climatic record in Gladwin County and by incompleteness of data and length of record for crops in all of the counties.

ANALYSIS OF CROP DATA

Yearly crop yields for each crop in each county are shown in Figure 6. These estimates were taken from annual crop reports published by the Michigan Agricultural Reporting Service and its predecessors, in cooperation with the USDA Statistical Reporting Service (Michigan Department of Agriculture, n.d.). Steyaert (1977) reported that these estimates were within 4 to 8% at the state level.





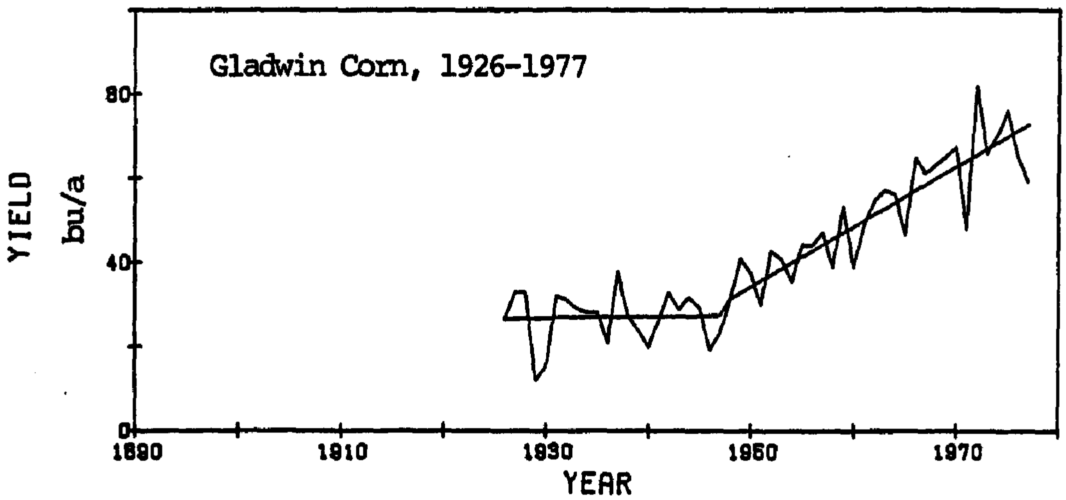
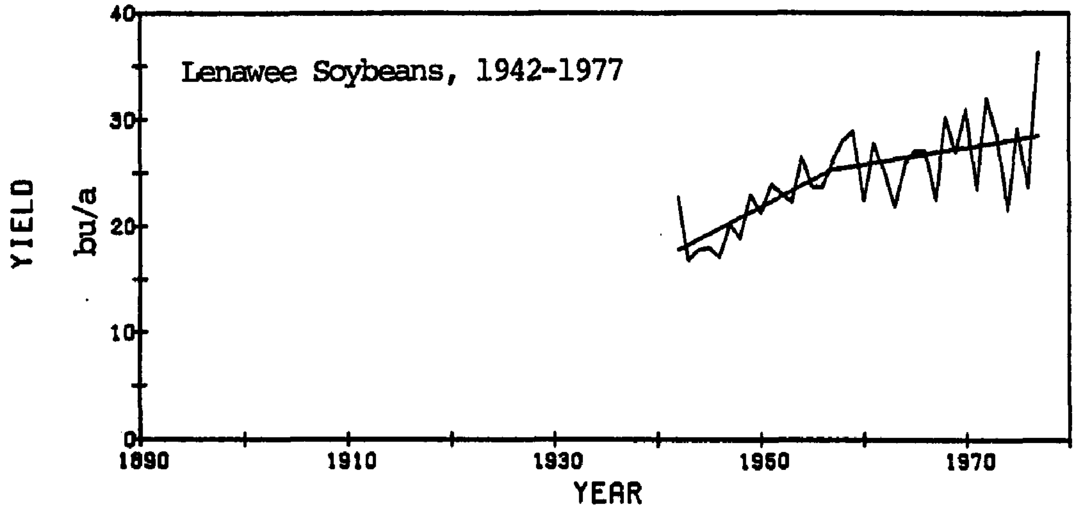
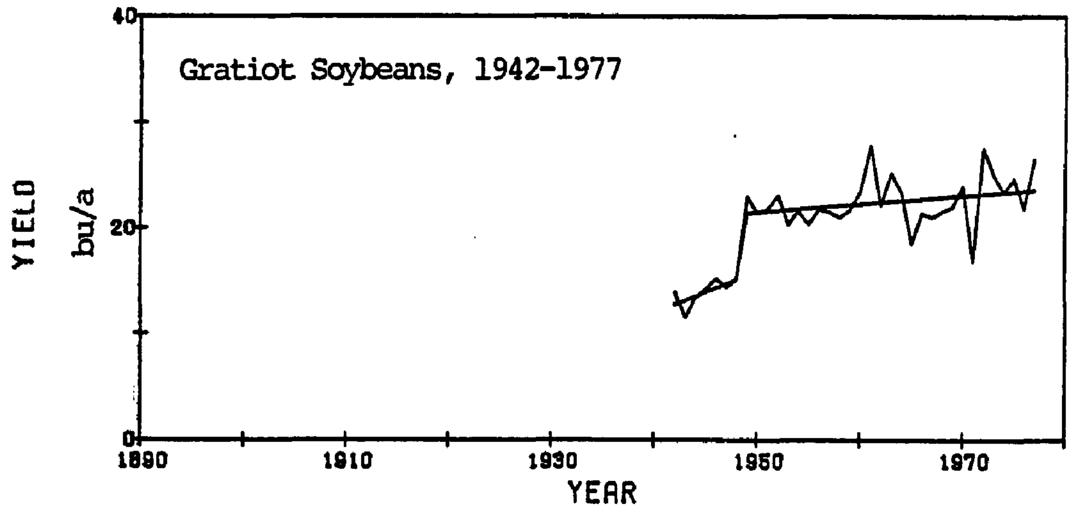


Figure 6. County Annual Yields, with Segmented Trend Lines.





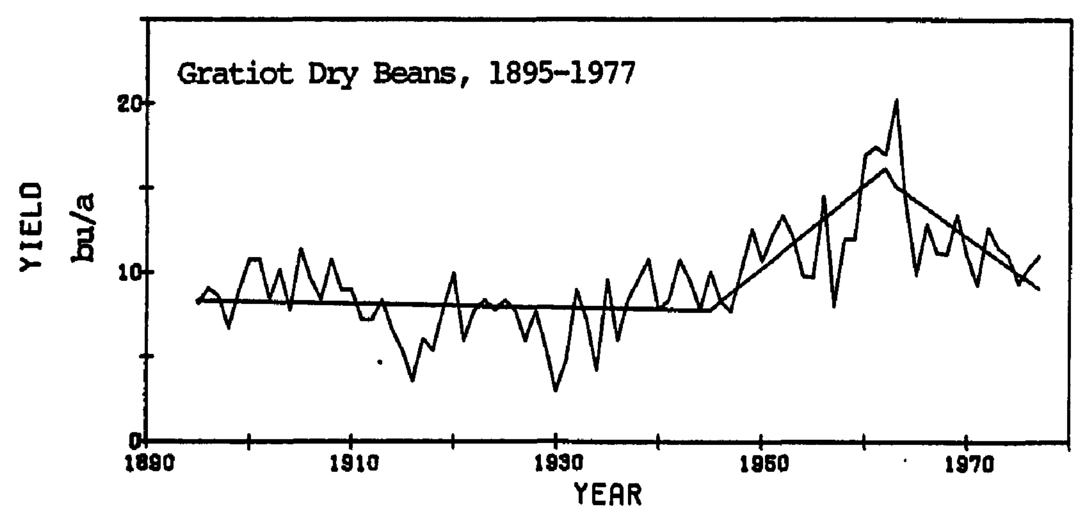
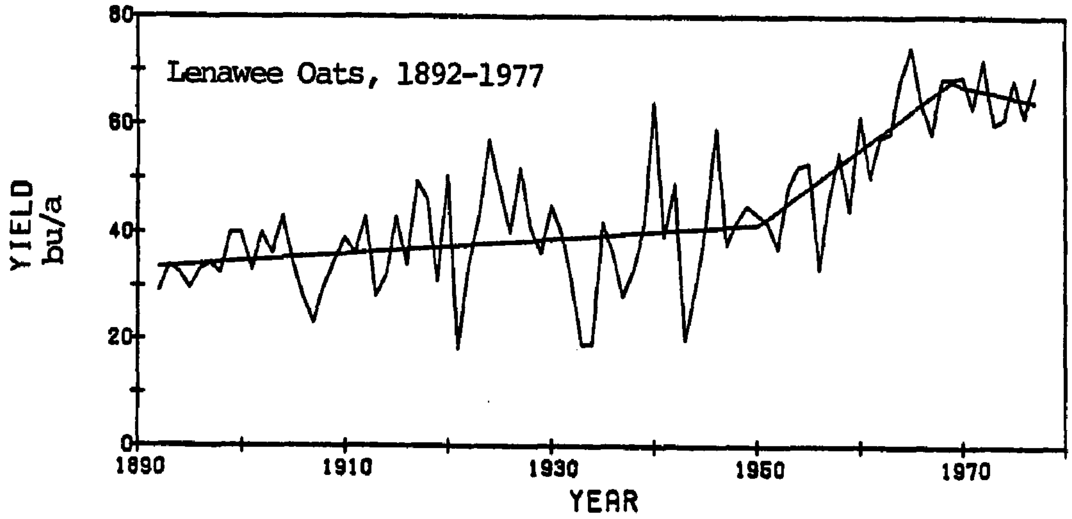
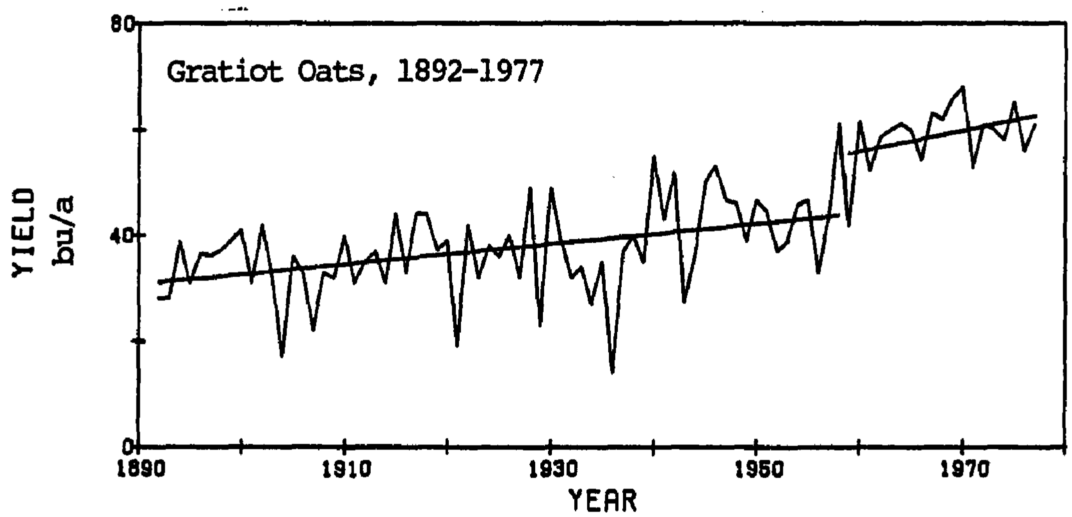


Figure 6. (continued)





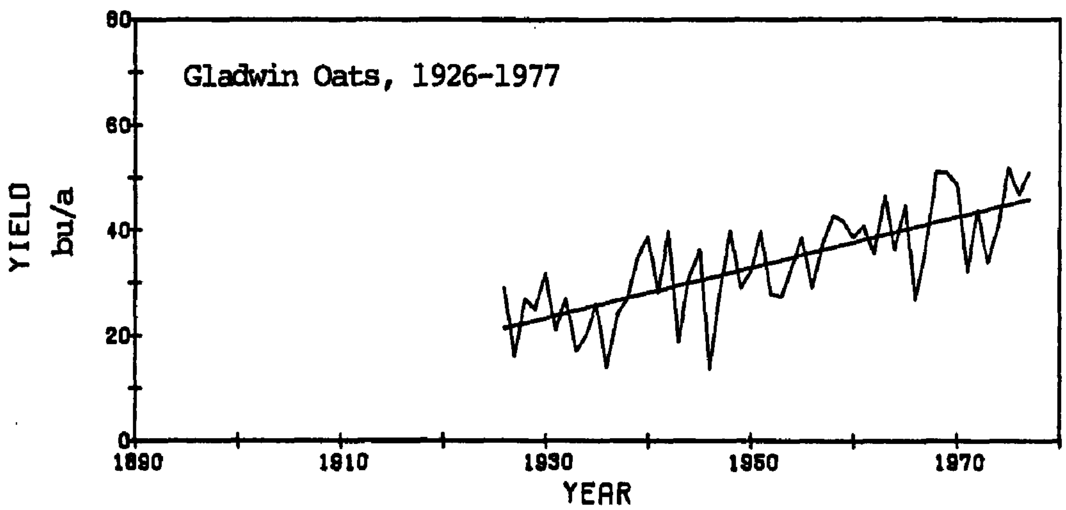


Figure 6. (continued)

Further adjustments, based on agricultural census data, are used to obtain county yield estimates. In addition to yields, segmented yield trends calculated by piecewise linear regressions are also shown.

YIELDS

CORN

Corn yields show the greatest increases. These increases began in Lenawee County around 1940, but Gratiot and Gladwin County corn yields did not begin to increase until nearly 1950. The rate of increase slowed about 1970. This slowing of yield increase is associated with a sharply increased year-to-year variability, in contrast to the relative stability of the previous twenty years.

SOYBEANS

Soybean yields in Lenawee County increased from 1942 to 1957. Since 1957 the rate of increase has slowed and variation about the trend line has increased. Gratiot County yields increased from 1942 to 1948. A definite and permanent jump in yields occurred in the 1959 data. The reason for this sharp change has not been determined, as the timing of the jump did not coincide with the timing of improved varieties or changes in cultural practices (Erdmann, 1979). A similar discontinuity did not appear in Lenawee County yields.

DRY BEANS

Gratiot County dry bean yields peaked at an all-time high of 20.3 cwt/a in 1963, and have shown a negative slope since. Yields continued to decrease to a 10.2 cwt/a average for the 1974-77 period. Gladwin yield records are missing from several years, including 1960-63, but show a similar but less rapid downward trend since that time in comparison with Gratiot County. State dry bean yields in 1979 increased to 14.0 cwt/a. Lenawee County dry bean records are omitted from the crop reports from 1949 through 1975, due to insufficient acreage, so no comparison can be made. However, average yields since 1964 have been at a level well above pre-1950 yields.

OATS

Oat yields are characterized by a much greater year-to-year variability than are corn yields. This is particularly true in the southern counties of Michigan. A distinct escalation in annual oat yields did not appear until the 1950s. In Gratiot County the increase appeared as an abrupt 20 bushel jump in 1958, dropping 22 bushels in 1959 and remaining at a level averaging 18 bushels higher since 1960. Increases in Gladwin County were more gradual.

The increase in Michigan oat yields is probably related to the introduction of later-maturing, higher-yielding varieties. However, at the same time rotation practices were changed, with better crop soils being used for continuous corn while the decreasing acreage of oats was relegated to poorer soils (Grafius, 1979).

LINEAR TRENDS

Changes in the level of crop yields over time are apparent. To clarify these trends, segmented linear regressions were fitted to each data set. The regression lines are shown in the yield diagrams, Figure 6. Judgment was applied in connecting the ends of adjacent pieces, without sacrificing the accuracy of trend values, to avoid excessive dislocation in the relative values of deviations from the trend line in adjacent years. This was possible with two exceptions. Gratiot oat yields had a 10-bushel discontinuity between 1958 and 1959, and Gratiot soybeans had a 7-bushel discontinuity between 1948 and 1949. Time periods and coefficients for the linear regression segments are shown in Table 3.

Deviations about the regression line represent shorter-term variations within the overall trend. These are considered to be primarily due to year-to-year changes in weather conditions, but are also affected by other uncontrolled variables. The long-term trends as shown by the regression lines are considered to be due to technological developments such as increased fertilizer use, improved varieties, higher plant populations, earlier planting, more effective pest control, and management application of these developments.

The deviation from long-term trend is obtained by subtracting the annual value of the trend line from the actual yield for that year. This residual value is processed as a signed number, positive when the actual yield is above the trend regression line and negative when it lies below. After the predicted annual deviations from the trend line are calculated by the multiple regression models, these

Table 3. Linear Regressions Used for Yield Trends

	Years	n[a]	a	b
Lenawee corn	1892-1940	49	31.60	.107
	1938-69	38	31.12	1.714
	1969-77	9	86.84	.087
Gratiot corn	1892-1944	53	34.67	- .007
	1942-63	22	29.03	2.036
	1962-77	16	74.02	.554
Gladwin corn	1926-48	23	26.56	.038
	1945-77	33	25.72	1.424
Lenawee soybeans	1942-57	16	17.27	.507
	1957-77	21	25.16	.162
Gratiot soybeans	1942-48	7	12.36	.400
	1949-77 [b]	29	21.36	.079
Gratiot dry beans	1895-1948	54	8.35	- .011
	1946-63	18	7.84	.492
	1961-77	17	16.44	- .432
Lenawee oats	1892-1950	59	33.38	.136
	1948-69	22	36.99	1.416
	1968-77	10	68.35	- .416
Gratiot oats	1892-1958	67	30.97	.190
	1957-77 [b]	19	55.08	.398
Gladwin oats	1926-77	52	20.91	.482

a) n's add to more than total years due to overlapping of regression equations. Lines are connected for best fit without overlap

b) discontinuity

Regression equation: $Y = a + bx$

x = nth year of record

annual residual values are added back into the linear trend value for that year to provide the predicted annual yield.

CROP ACREAGES

A study of yields cannot be separated from a consideration of acreages for the crops studied. Average yield may be affected by relative quality and yield potential of land used; by institutional constraints such as government conservation and control programs; and by shifts between different crops.

Four questions emerged in regard to crop acreages: (1) What was the pattern of acreage over time in the four crops studied? (2) Did soybeans replace corn? (3) Was there a shift between dry beans and soybeans? and (4) What happened to oat acreages, and why? Acreage figures for these crops were available for the years 1942-1977, and are shown in Figure 7.

Corn acreage increased through the 1950s, except for Gladwin County. Government soil bank acreage reserve programs went into operation in the late 1950s. Corn acreage began a downward trend at that time, except for a one-year increase in 1959. This downward trend in corn continued through the 1960s, followed by an increase in the 1970s. Soybean acreage increased steadily from the early 1950s into the 1970s, especially in Lenawee County. Gratiot dry bean acreage lagged yield trends, increasing into the mid-1960s, then dropping off. Oats dropped during the 1950s and 1960s to only one-third to one-tenth of acreages in the late 1940s.

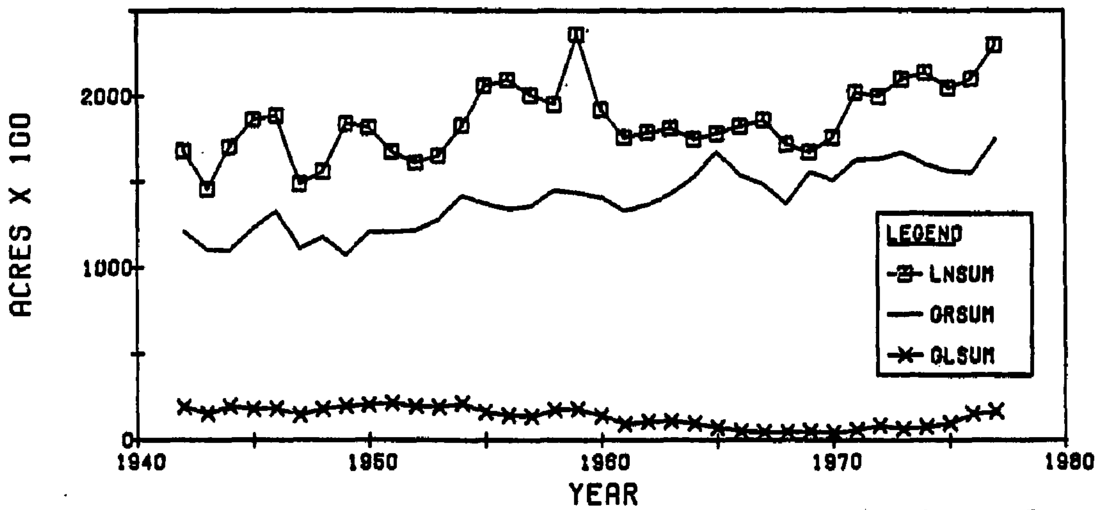


Figure 7a. Total County Acreages of Crops in the Study.

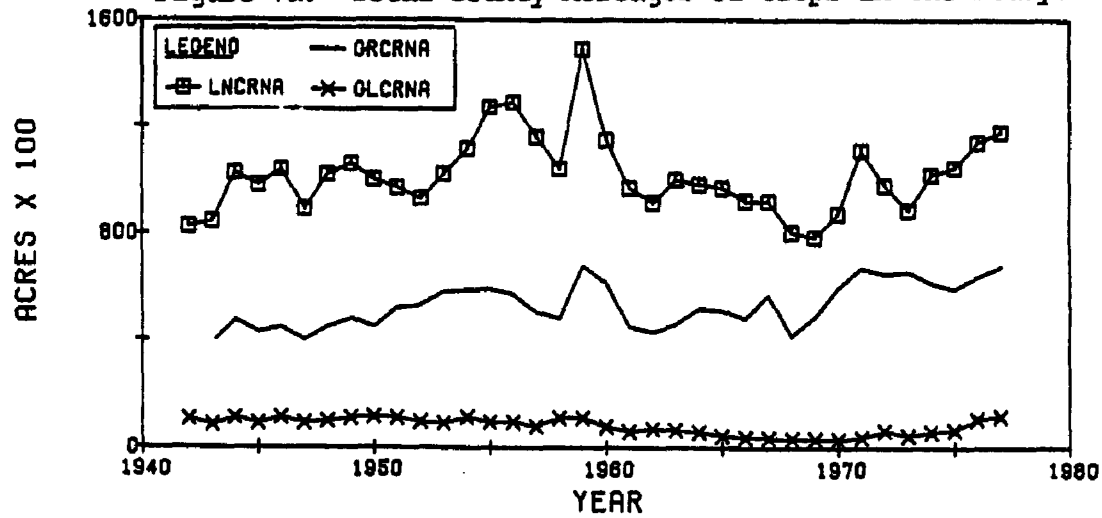


Figure 7b. Corn Acreage by County, 1942-1977.

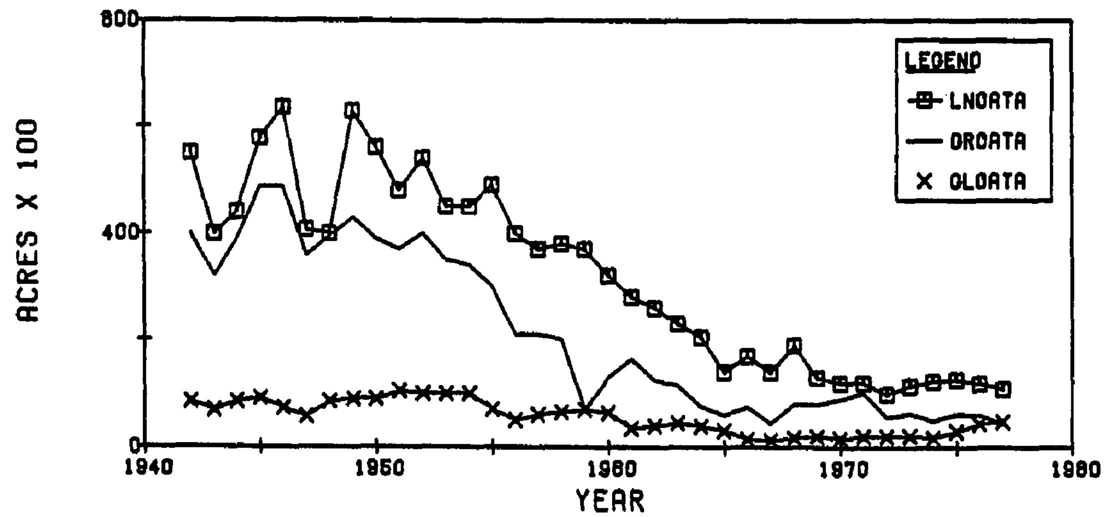


Figure 7c. Oat Acreage by County, 1942-1977.

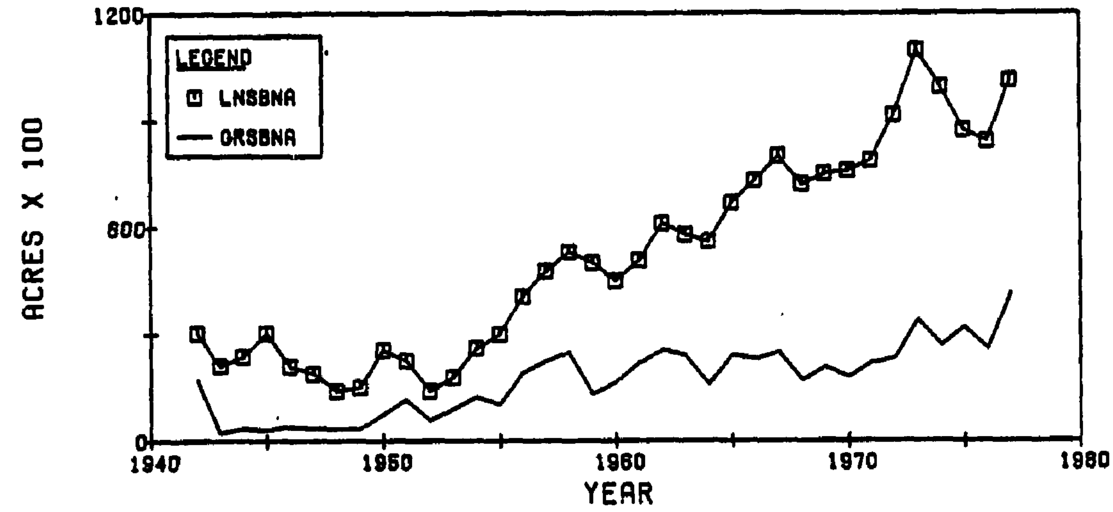


Figure 7d. Soybean Acreage, Lenawee and Gratiot Counties, 1942-1977.

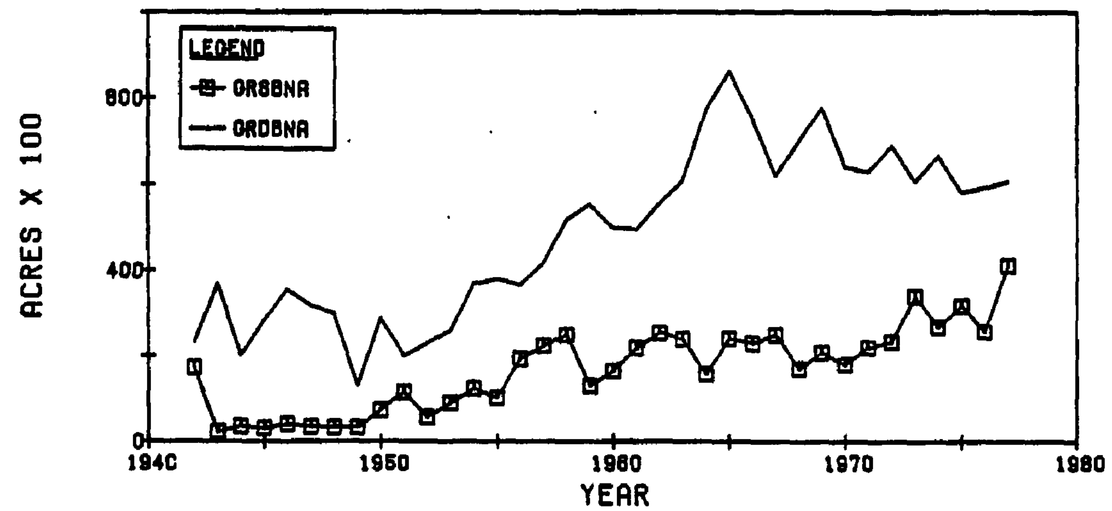


Figure 7e. Dry Bean and Soybean Acreage, Gratiot County, 1942-1977.

In Lenawee County, a 40,000 acre decrease in corn acreage in the 1960s was more than balanced by an increase in soybeans. A 20,000 acre drop in corn in Gratiot County was not matched by an increase in soybeans, whose acreage was almost constant in the 1960s. In the 1970s a 15,000 acre decline in dry beans grown in Gratiot County was followed, with a two to three year lag, by a similar but not parallel increase in soybeans.

Oat acreage declined sharply in the 1950s in Gratiot County and into the mid-1960s in Lenawee County. Lenawee oat acreage dropped from 63,000 acres in 1949 to 10,000 acres in 1972, while Gratiot oat acreage dropped from a high of 49,000 acres in 1945 and 1946 to less than 5000 acres in 1977. Gladwin oat acreage decreased from over 10,000 acres in 1952 to 1300 acres in 1967; it has since edged up to 4800 acres in 1977.

CHAPTER IV

ANALYSIS OF CLIMATE-YIELD RELATIONSHIPS

The primary goal of this research is to improve our understanding of relationships which exist between climate in the growing season and yields obtained from field crops. Multiple regression analysis was used to determine some of these relationships. Separate analyses were made with climatic data on monthly and weekly time scales.

ANALYSIS BASED ON MONTHLY DATA

Multiple regressions were run on each crop studied in each county. The dependent variable in each case was crop yield deviation from the trend line. The independent variables were average monthly temperatures, total monthly precipitation (or non-excess precipitation), and a moisture availability index (based on either actual or non-excess precipitation). These three variables were also squared, for three additional variables. For corn, soybeans, and dry beans, the growing season months of April through September were included in the regression. The three variables plus three squared terms, for each of six months, resulted in a multiple regression with 36 possible independent variables. Due to the August harvest for oats, the regression for oats included only April through August, or 30 possible variables.

Each county and each crop was treated separately for actual precipitation and for two versions of non-excess precipitation. The latter excluded any amount in excess of one inch and two inches in a single calendar day. In the latter cases, non-excess precipitation was also used in development of the moisture availability variable.

RESULTS OF THE MONTHLY ANALYSIS

SIMPLE CORRELATION

Simple correlation coefficients (r values) between crop yield deviations from trend and monthly climatic variables are given in Table 4. Caution is urged in the use of these figures. For corn, soybeans, and dry beans the critical r value for the 5% significance level is 0.320. Thus for a single crop/county case, it would require that two or more of the 36 variables (6 variables for 6 months) must have r values above 0.32 in order to be statistically signicant at the 5% level. For oats the critical r value is 0.361. Use of these r values should be combined with an understanding of the physical principles of plant response to the environment.

MULTIPLE REGRESSION ANALYSIS

The predictor equations for each of the 9 county/crop cases, with variables selected, are shown in Table 5. For corn, soybeans, and dry beans there are six possible variables in any of the six months of the growing season, or 36 possible variables out of which the stepwise multiple regression analysis could select the most strongly related. For oats, there are 30 possible variables. The distribution of the variable selection for each crop is shown in

Table 4. Simple Correlations (r) for Yields and Monthly Climate Variables

	CORN			OATS			SOYBEANS		DRY BEANS
Variable	Len	Gra	Gla	Len	Gra	Gla	Len	Gra (a)	Gra
April Temp	.10	-.02	-.08	.03	.27	.17	.10	.06	.02
May "	.20	.06	.01	-.13	-.08	.16	.40	.13	-.03
June "	-.12	.14	.06	-.42	-.29	-.35	-.17	-.22	.01
July "	-.09	.10	.16	-.26	-.27	-.08	.15	.20	-.11
Aug "	-.08	.16	.17	-.23	-.04	.08	.12	-.10	-.01
Sept "	.13	.12	-.21	—	—	—	.18	-.01	-.13
April Prec	.02	-.08	-.17	-.31	.15	-.001	.23	-.16	-.07
May "	-.18	-.05	.08	-.32	.12	.05	-.09	-.10	.07
June "	.01	.07	.04	-.04	.17	.30	-.04	-.02	-.03
July "	.26	.22	.33	-.05	-.03	.05	.32	.27	.23
Aug "	.34	.27	.25	.13	.01	.18	.48	.42	.29
Sept "	.14	.03	-.12	—	—	—	.23	.19	-.02
April MAI (b)	-.004	-.07	-.14	-.30	-.22	-.05	.23	-.16	-.07
May "	-.18	-.09	-.04	-.39	-.03	-.03	-.01	-.21	.01
June "	-.11	-.06	-.01	-.26	.10	.18	-.01	-.12	-.01
July "	.04	.03	.14	-.20	.10	.19	.11	-.04	.11
Aug "	.16	.12	.23	-.12	.10	.26	.32	.19	.24
Sept "	.18	.11	.19	—	—	—	.34	.24	.22
April Temp Sq	.11	-.02	-.08	.03	.27	.18	.10	.06	.02
May " "	.20	.05	.006	-.13	-.08	.16	.40	.13	-.04
June " "	-.12	.14	.06	-.43	-.30	-.36	-.17	-.22	.005
July " "	-.09	.10	.16	-.26	-.30	-.08	.15	.19	-.11
Aug " "	-.09	.15	.17	-.23	-.04	.08	.11	-.10	-.01
Sept " "	.13	.12	-.20	—	—	—	.17	-.004	-.13
April Prec Sq	.03	-.07	-.23	-.28	-.11	-.01	.20	-.18	-.07
May " "	-.19	-.11	.04	-.31	.04	-.004	-.08	-.08	.06
June " "	-.04	.05	.04	-.11	.15	.25	-.10	-.06	-.03
July " "	.16	.18	.30	-.04	.02	.01	.28	.22	.16
Aug " "	.28	.27	.27	.13	.04	.17	.42	.40	.20
Sept " "	.15	.02	-.10	—	—	—	.23	.19	.03
April MAI Sq	-.000	-.07	-.15	-.29	-.21	-.04	.23	-.17	-.07
May " "	-.18	-.12	-.09	-.39	-.05	-.04	-.02	-.19	.01
June " "	-.14	-.09	-.06	-.28	.08	.18	-.04	.13	-.02
July " "	-.02	-.03	.09	-.25	.08	.18	.09	-.06	.08
Aug " "	.07	.05	.21	-.19	.09	.23	.29	.13	.18
Sept " "	.08	.05	.12	—	—	—	.31	.17	.18

(a) Non-excess precipitation for Gratiot soybeans

(b) MAI: Moisture Availability Index

Table 5. Multiple Regression Models, Monthly Data

Crop	n	R^2	s.e.	
LENAWEE				
Corn	86	.42	6.45	$\hat{Y}$= - 36.32 + 4.91xAUGP + 4.91xJULP - 0.40xJLPQ - .0092xAGMAQ + 0.40xSPMAI + .0036xSPTQ - 0.44xAGPQ
Soybeans	36	.56	2.14	$\hat{Y}$= - 48.24 + 1.07xAUGP + 0.79xJULP + 0.45xJULT + 0.55xSEPP + 0.18xAPRT
Oats	86	.36	6.81	$\hat{Y}$= 85.14 - .006xJNTQ - 0.55xMYMAI - .0036xMYTQ - .0035xJLTQ
GRATIOT				
Corn	86	.15	6.96	$\hat{Y}$= - 38.06 + 0.13xAGPQ + 1.17xJULP + 0.53xSEPT
Dry Beans (cwt.)	83	.21	1.87	$\hat{Y}$= - 3.81 + 0.86xAUGP + 1.12xJULP - 0.12xJLPQ - .068xAGPQ
Soybeans NXSP	36	.35	1.80	$\hat{Y}$= - 10.33 + 1.09xAUGP + 0.69xJULP + 0.20xAPRT - .0011xMYTQ
Oats	86	.33	6.28	$\hat{Y}$= 18.52 - .0023xJNTQ + 0.85xAPRT - .0082xJLTQ - 1.25xAPRP - 1.01xJUNP
GLADWIN				
Corn	52	.47	5.23	$\hat{Y}$= -135.08 + 0.99xJULP - 0.18xAPPQ + 0.35xAGPQ + 4.47xMYMAI - 0.47xMYMAQ + 0.95xJULT - 2.64xAUGP - 0.55xSEPT
Oats	52	.39	5.71	$\hat{Y}$= -346.49 - .0070xJNTQ + .0073xAPTQ + 0.67xAUGP + 1.34xJUNP + 12.22xMAYT - 0.10xMYTQ

Note: 1) NXSP=non-excess precipitation (excess over 1"/day is removed)
2) MAI= Moisture Availability Index
3) Q indicates a squared term

Table 6. Also shown is a combined selection density chart, with variables coded by crop.

For corn, soybeans, and dry beans, the most significant (selected first by the stepwise regression) and consistent variables were the July and August precipitation. There were three corn, two soybean, and one dry bean cases, or six equations. For these six cases a total of 31 variables were selected by the six regression analyses. Of these 31, 17 were July and August precipitation variables, including the squared terms. The other 14 were scattered over 12 other non-precipitation variables.

For the three oat equations with a total of 15 selected variables, the square term for June temperature was selected in all three cases. May and July squared temperatures and June precipitation were selected in two out of the three cases. The other six were scattered, as shown in Table 6.

The moisture availability term appeared to be of little importance. It did not appear at all in the soybean or dry bean equations. It appeared only once in oats, in Lenawee County as May MAI. It appeared also in Gladwin County corn in May, in both squared and unsquared terms. In total, moisture availability appeared only five times out of a total of 44 variables selected. Correlations with yields are negative in the early part of the season, indicating that planting delays in May due to wet field conditions may tend to decrease yields.

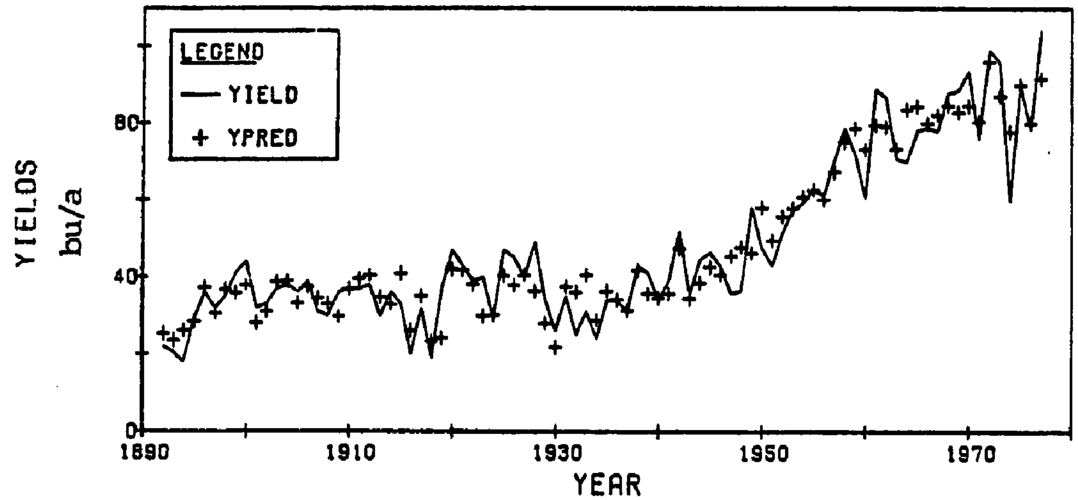
Actual and predicted yields, based on monthly climatic data are shown in Figure 8.

Table 6. County Climate Variables Selected by Month-Based Multiple Regression Crop Models

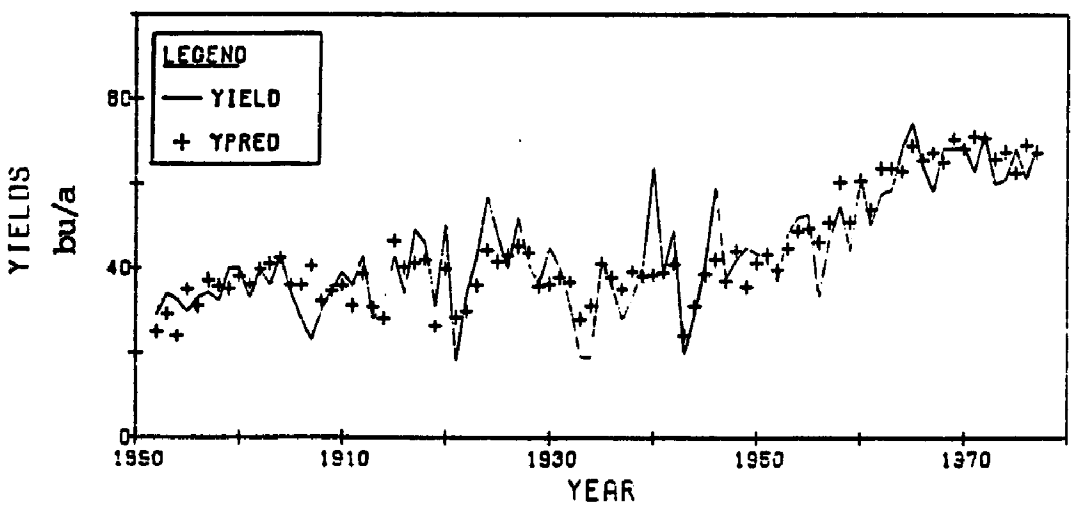
	CORN						DRY BEANS						SOYBEANS						OATS					
	T	T^2	P	P^2	M	M^2	T	T^2	P	P^2	M	M^2	T	T^2	P	P^2	M	M^2	T	T^2	P	P^2	M	M^2
Apr				Gl									Ln Gr						Gr	Gl	Gr			
May					Gl	Gl								Gr					Gl	Ln Gl			Ln	
Jun																				Ln Gr Gl	Gr Gl			
Jul	Gl		Ln Gr Gl	Ln					Gr	Gr			Ln		Ln Gr					Ln Gr				
Aug			Ln Gl	Ln Gr Gl		Ln			Gr	Gr					Ln Gr						Gl			
Sep	Gr Gl	Ln			Ln										Ln									

T: Temperature P: Precipitation M: Moisture Availability Index

Ln: Lenawee County Gr: Gratiot County Gl: Gladwin County

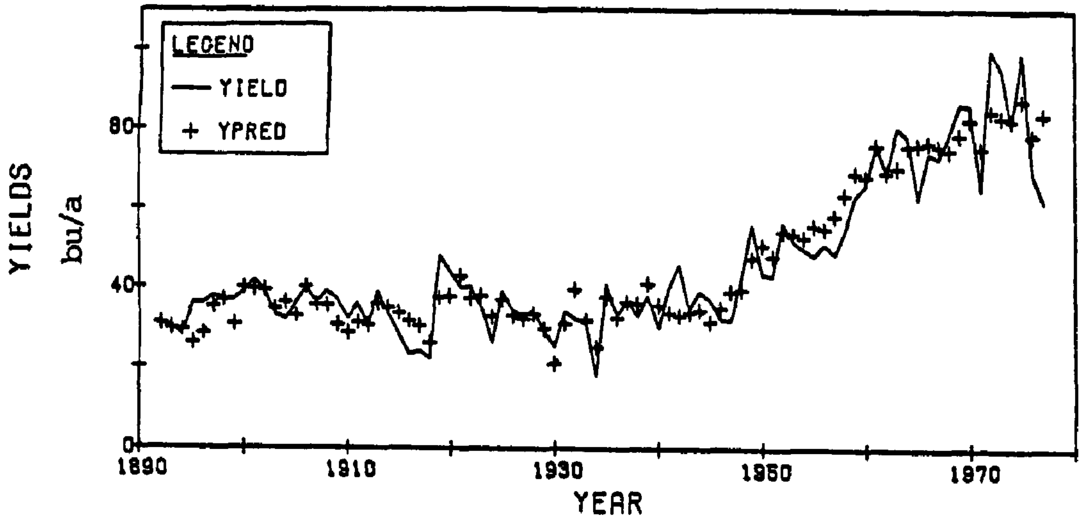


a. Corn Yields, Lenawee County, 1892-1977

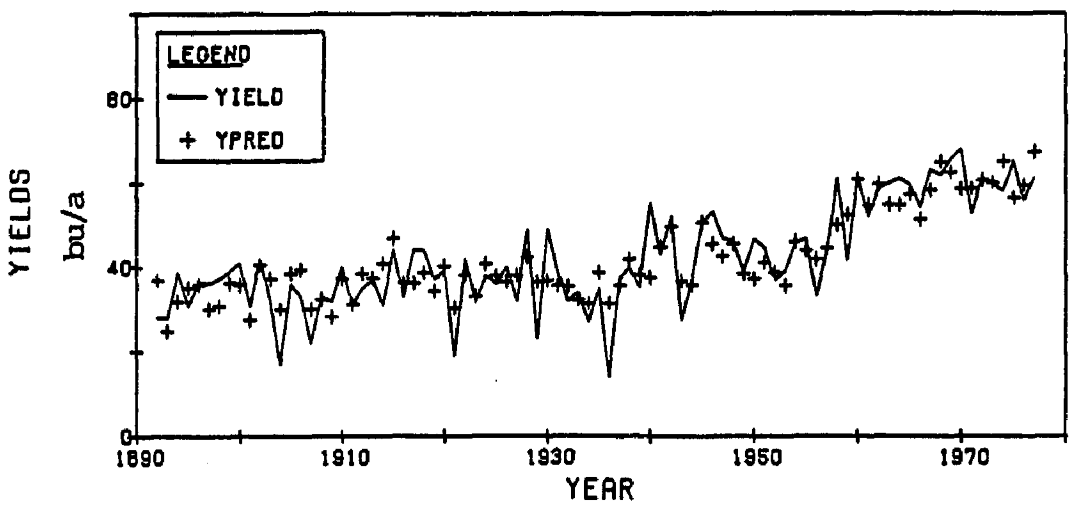


b. Oat Yields, Lenawee County, 1892-1977.

Figure 8. Actual and Predicted Yields Based on Monthly Climate Data.

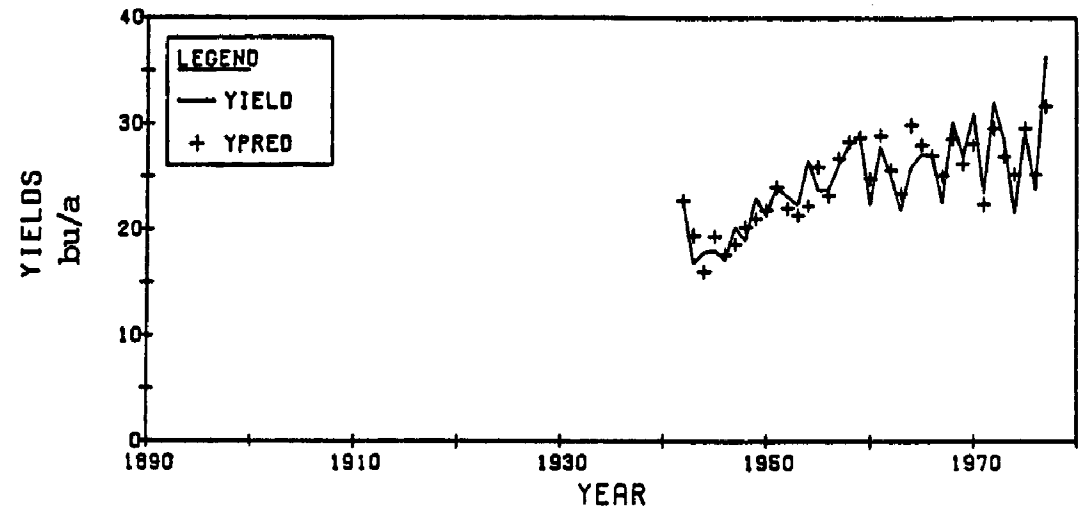


c. Corn Yields, Gratiot County, 1892-1977

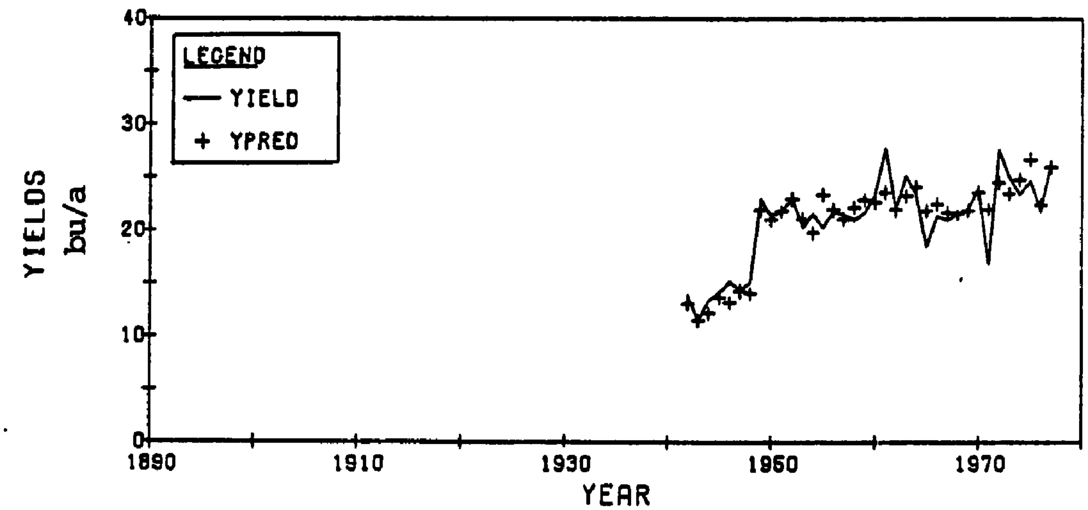


d. Oat Yields, Gratiot County, 1892-1977

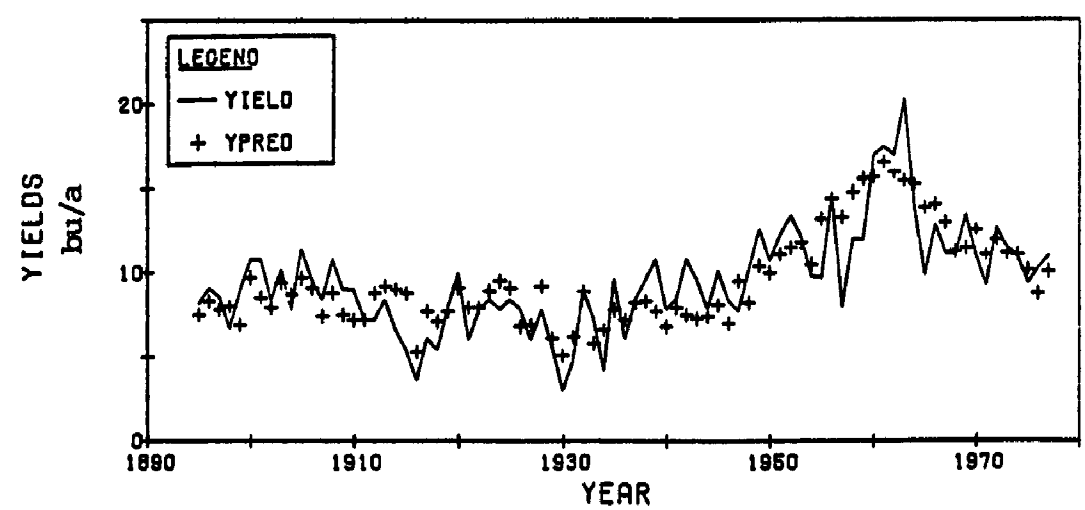
Figure 8. (Continued)



e. Soybean Yields, Lenawee County, 1942-1977

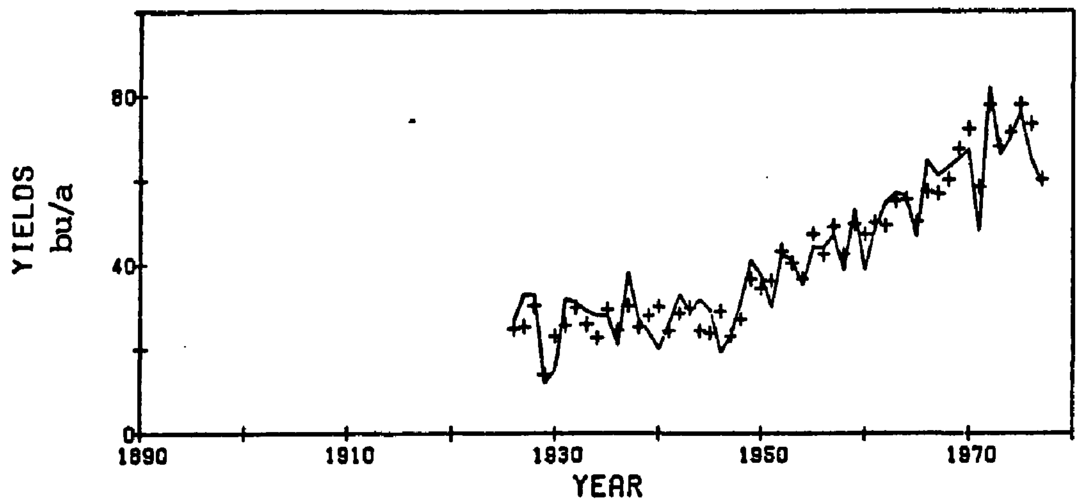


f. Soybean Yields, Gratiot County, 1942-1977

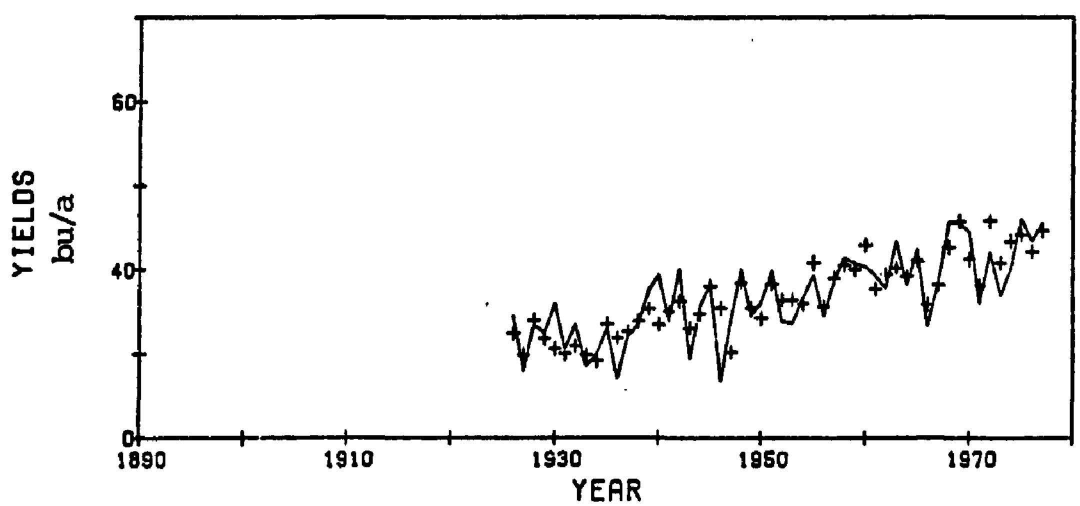


g. Dry Bean Yields, Gratiot County, 1895-1977.

Figure 8. (Continued)



h. Corn Yields, Gladwin County, 1926-1977



i. Oat Yields, Gladwin County, 1926-1977

Figure 8. (Continued)

RESULTS WITH NON-EXCESS PRECIPITATION DATA

Separate multiple regressions were run for all nine county/crop cases with excess precipitation removed. The first set of runs limited precipitation by removing all precipitation in excess of one inch per calendar day. The second set removed all over two inches per day. The non-excess precipitation term was used in the development of the moisture availability variables for these runs. The statistics for all month-based regressions are shown in Table 7. In most cases, the results in terms of R^2 values obtained under identical restraints differed little from the regressions in which actual precipitation was used. Gladwin corn showed an R^2 drop from .47 with actual precipitation to .20 and .25 for non-excess versions. Gratiot soybeans improved from an R^2 of .23 with actual precipitation to .32 with precipitation over one inch per day removed. Removing two inches returned the R^2 to .26. Removal of excess rainfall as tested above appeared to be of little value in the analysis.

ANALYSIS OF OUTLYING YIELDS

Why do some years show unusually high or low yields in a specific crop? A qualitative effort was made to determine differences in weather conditions in these exceptional years.

SELECTION OF OUTLIERS

For each crop/county case, years with extreme yields, i.e., yields farthest from the trend line, were studied. Since using all occurrences outside of one standard deviation was unwieldy and using

Table 7. Statistics from Multiple Regression, Actual and Non-Excess Precipitation, Monthly Data

Crop	Actual Precipitation			not in excess of 1"/day			not in excess of 2"/day		
	n vars.	R^2	s.e.	n vars	R^2	s.e.	n vars	R^2	s.e.
Lenawee corn	7	.42	6.45	6	.40	6.53	6	.41	6.46
Gratiot corn	3	.15	6.96	3	.15	6.93	3	.16	6.89
Gladwin corn	8	.47	5.23	4	.20	6.15	4	.25	5.97
Lenawee soybeans	5	.56	2.14	4	.52	2.21	5	.57	2.12
Gratiot soybeans	3	.23	1.93	3	.32	1.83	3	.26	1.90
Gratiot dry beans	4	.21	1.87	2	.21	1.84	4	.21	1.88
Lenawee oats	4	.36	6.81	4	.36	6.81	4	.36	6.80
Gratiot oats	5	.33	6.28	5	.31	6.35	5	.33	6.28
Gladwin oats	6	.39	5.66	5	.37	5.71	7	.43	5.56

all outside two s.d.'s provided too few cases, the number of occurrences outlying with approximately 10% of the yields for each case was used. This cut-off point in yield units, number of cases, and percent of total are shown in Table 8.

PLOTS OF OUTLIERS

Yield outliers were plotted on a 4-quadrant X-Y plot with the intersection at (0,0). Each of the four crops with all counties combined was plotted for each month of the growing season. Figure 9 shows positve and negative departures from the yield trend lines for each growing season month for all years in the period of record in which the yield of any specific crop is an outlier. Departures of temperature and precipitation from long-term climatic normals are missing in some cases. For corn, this includes 1894 and 1928 plus August and September of 1916 and May of 1918 for Lenawee County, and April of 1977 for Gladwin County. For oats, 1904 Gratiot data and 1936 Gladwin data are missing. The X-axis is scaled for temperatures cooler to warmer than the existing climatic normals as given in the official annual climatic summaries for Michigan. The Y-axis is scaled from wetter to drier than normal. Scale in all cases is the same, as shown in the legend. Sign of the yield departure from trend for the years of yield outliers is plotted at the appropriate X-Y coordinates.

Table 8. Data for Yield Outliers, Based on Monthly Climate Data

COUNTY	CROP	CUTOFF	NUMBER	% OF TOTAL
Lenawee	Corn	13 bu.	8	9.3
	Soybeans	5 bu	3	8.3
	Oats	14 bu.	8	9.3
Gratiot	Corn	13 bu.	8	9.3
	Dry beans	3 cwt	9	10.8
	Soybeans	4 bu.	4	11.0
	Oats	12 bu.	8	9.3
Gladwin	Corn	11 bu.	5	9.7
	Oats	11 bu.	4	7.7

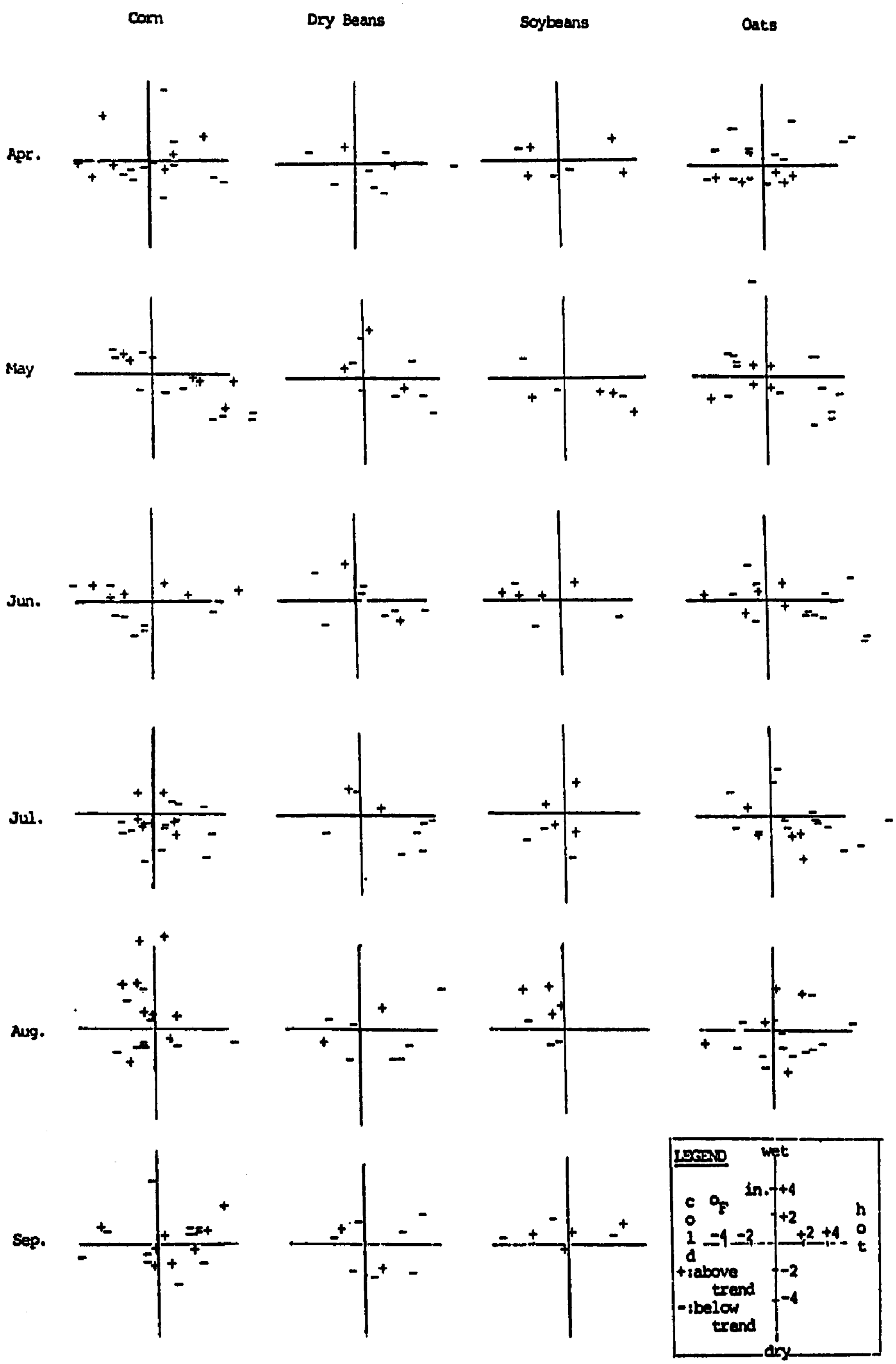


Figure 9. Signs of Yearly Departures over 10% from Yield Trend, with Monthly Climates.

RESULTS OF OUTLIER ANALYSIS

Results appearing in the different plots were qualitatively evaluated by position of the outlying yield cases relative to the cool vs. warm and wet vs. dry axes of the chart.

CORN

Lower yields were associated with drier July and August weather. Higher yields occurred in wetter Augusts. September showed no consistent pattern.

DRY BEANS

These showed no consistent pattern. Lower yields appeared mostly when July was hot and dry. Higher yields appeared only when July was wetter than normal.

SOYBEANS

These also showed no definite pattern. All low yields appeared when July was dry. All outliers, both positive and negative, appeared in cooler than normal Augusts, with higher yields associated with more moisture.

OATS

Higher oat yields were associated with wet Aprils, and with warmer temperatures than usual in May, June, and July, with a few exceptions. Higher yields appeared when Aprils were slightly drier than usual.

ANALYSIS OF YIELDS CLOSE TO THE TREND LINE

To gain perspective on climatic variations with yield, "inliers" were checked for corn. These were the 8 to 10% of the years in which yields fell closest to the trend line for those years.

Climatic conditions for those years were scattered in much the same manner as outlier years. "Normal" corn years tended toward dry and/or warm average weather in August. September weather was scattered in all directions.

ANALYSIS BASED ON WEEKLY DATA

The majority of the Thompson-type statistical crop-weather models reported in the literature use monthly weather data, as does the preceding part of this study. Climate data on a monthly scale, while more widely available, tend to dilute the discernable impacts of weather events and conditions on critical stages of plant growth. This portion of the study deals with a multiple regression analysis of climate and yields using weekly temperature and precipitation data.

METHOD

The weekly analysis was applied to data from Lenawee and Gratiot Counties for the years 1943 through 1977. Weekly data covers the period from the week ending March 7, designated as week 01, through October 31, ending week 35. Ending dates of the weeks in the analysis are shown in Table 10.

The weekly-based climate-yield analysis uses the same approach of applying multiple regression to de-trended yields as was used in the monthly-based analysis. Independent variables are the mean weekly temperatures and total weekly precipitation.

The growing season period from week 08 through week 32, or April 19 through October 10, was used for corn, soybeans, and dry beans. For oats, the period used was week 06 through week 24, or April 5 through August 15. For Gratiot oats, improved R^2 values were obtained by summing the temperatures of weeks 16 and 17 into a new variable, TMP67.

While the Michigan Agricultural Reporting Service uses sampling-based objective techniques for mid-season prediction of the current year's yields, a supplemental weather-based predictive model may prove useful. Accordingly, a mid-season regression model was run for each crop/county case. The corn, soybean, and dry bean models were truncated at week 24 (August 15), and the oat model at week 17 (June 27). Truncation points were based on the distribution of variables selected by the full-season regression analysis, which is shown in Table 9.

RESULTS OF THE WEEKLY ANALYSIS

SIMPLE CORRELATION

Simple correlation coefficients (r values) between yield deviations from trend and weekly temperatures and precipitation for each crop/county case are shown in Table 10. For corn, soybeans, and dry beans the critical value for the 5% significance level is

Table 9. Distribution of Climate Variables Selected by Week-Based Regression Models

	R^2	s.e.		06	07	08	09	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32
																	WEEK													
LENAWEE																														
Corn	.71	5.5	T																											x
			P										x							x	x	x					x			
Soybeans	.58	2.0	T											x				x										x		
			P																					x			x			
Oats	.82	3.6	T					x				x	x																	
			P				x	x		x					x				x											
GRATIOT																														
Corn	.52	6.7	T															x												
			P											x					x	x										
Dry beans	.61	1.5	T																				x							
			P						x								x	x				x								
Soybeans	.71	1.3	T											x					x	x										
			P											x							x						x			x
Oats	.41	5.2	T									x		x	x															
			P																		x									

Table 10. Correlations of Deviations from Yield Trends and Weekly Climate Variables

Week, Ending			Corn				Soybeans				Dry Beans		Oats			
			Len		Gra		Len		Gra		Gra		Len		Gra	
			T	P	T	P	T	P	T	P	T	P	T	P	T	P
06	Apr.	11											.16	−.15	.22	.32
07		18											.30	−.09	.18	−.03
08		25	.20	.35	−.16	−.18	.15	.40	.14	−.003	−.11	−.25	.26	.01	.09	.16
09	May	2	.01	.02	.11	.22	.18	.10	.13	.07	−.16	.14	.13	−.17	.15	−.22
10		9	.22	−.03	.15	−.04	.17	−.27	.03	−.04	.003	.29	.22	−.30	−.10	−.13
11		16	.34	−.28	−.15	−.05	.28	−.18	.05	−.03	−.15	−.04	.01	−.19	−.01	−.17
12		23	.14	.002	−.04	−.10	.31	.07	.13	−.22	.03	−.07	.21	−.38	−.02	.08
13		30	.24	.001	.06	.01	.22	.08	.13	−.11	−.03	−.07	−.002	−.10	−.08	.10
14	June	6	−.03	−.01	.19	.11	−.14	−.07	−.03	.06	.11	.05	−.37	−.16	−.44	.33
15		13	−.07	−.24	.05	−.13	−.17	−.20	−.14	−.19	−.21	−.13	−.31	.15	−.23	.18
16		20	.07	−.001	.06	.39	−.03	−.02	−.15	.40	−.08	.11	−.32	−.07	−.41	.08
17		27	−.26	.02	−.06	−.04	−.17	.03	−.27	−.13	.08	−.33	−.26	−.12	−.46	.08
18	July	4	−.02	.18	.26	−.38	.01	.03	.08	−.13	.03	−.02	.13	.05	−.05	.02
19		11	−.05	−.09	−.21	−.20	−.08	.16	−.16	−.07	−.06	−.43	−.03	−.05	−.12	.06
20		18	.02	.06	.10	.28	.36	.12	.10	.29	.07	.36	.03	−.25	−.14	−.15
21		25	.18	.06	.29	.38	.02	.27	.29	.28	.21	.14	.10	−.09	−.15	−.02
22	Aug.	1	−.06	.28	.24	.30	.01	.12	.17	.11	−.04	.14	−.12	−.09	.05	−.06

Table 10. (Cont'd.)

Week, Ending			Corn				Soybeans				Dry Beans		Oats			
			Len		Gra		Len		Gra		Gra		Len		Gra	
			T	P	T	P	T	P	T	P	T	P	T	P	T	P
23	Aug.	8	.14	.55	-.06	.37	.06	.35	-.03	.39	-.22	.30	-.09	.11	.12	-.20
24		15	.02	-.07	.03	.06	.11	.05	-.19	.26	-.18	.42	-.43	.02	-.23	-.13
25		22	-.19	.16	.07	.31	-.05	.32	-.24	.06	-.29	-.18				
26		29	-.02	.30	.27	.07	.17	.34	.09	.37	.08	.13				
27	Sep.	5	.23	.15	.13	.02	.21	.17	.01	-.11	-.06	-.19				
28		12	-.22	-.29	-.09	-.13	-.06	-.23	.08	-.21	.02	-.08				
29		19	.05	.40	-.25	-.11	-.01	.47	-.19	.37	-.23	.17				
30		26	.36	.11	.12	-.25	.44	-.05	.25	-.03	-.17	-.26				
31	Oct.	3	-.10	.05	.01	-.14	-.05	.03	-.32	.05	.04	.11				
32		10	.25	.03	.25	-.27	.0002	.25	.11	-.32	-.01	-.26				

Len: Lenawee County

Gra: Gratiot County

T : Temperature

P : Precipitation

.396. Expected frequency of variable occurrence above the critical r value for each case is 1.25. Thus in order to be significant at the 5% level a given crop would need an r value above .396 for two or more weeks for a given variable, out of the 35 weeks of data for that variable. For oats the critical r value is .456, with an expected occurrence of 0.95 per case. Since the number of crop/county variables exceeding the critical value ranges from zero to two, with a mean of 0.57, it is obvious that the r values in the table must be used with extreme caution.

MULTIPLE REGRESSION ANALYSIS

Predictor equations for full-season and mid-season models with selected variables are shown in Table 11. Improved accuracy from the weekly scale of data allowed individual variables to be restricted to the .05 level of significance or better.

Distribution of variables selected by the full-season models is shown in Table 9. We note that with the exception of 11th week precipitation for dry beans, no variables earlier than the 15th week (June 13) were selected by the stepwise regression for corn, dry beans, or soybeans. Earliest variable selected for oats was the 9th week (May 2) precipitation.

Runge and Benci (1975) used a simulation model to compare corn yields in Iowa and Missouri for 1972 and 1975. Variations in predicted yields did not show up until the week of June 24. Nearly all of the weather effect on yield had occurred by the week of August 5. This period is equivalent to our 16th through 23d weeks.

Table 11. Full- and Mid-Season models; Weekly Data, 5% Significance Level

Crop	Week	R^2	Std.error of est.	
LENAWEE				
Corn	08-32	.71	5.5	$\hat{Y}$= −51.23 + 8.84xP23 + 3.21xP29 + 5.46xP22 + 0.73xT32 − 5.89xP15 + 5.09xP24
	08-24	.40	7.4	$\hat{Y}$= − 9.90 + 9.72xP23 + 5.22xP22
Soybeans	08-32	.58	2.0	$\hat{Y}$= −55.50 + 1.05xP29 + 0.21xT30 + 0.40xT20 + 0.18xT16 + 1.31xP26
	08-24	.39	2.4	$\hat{Y}$= 0.99 + 1.68xP08 − 2.14xP15 − 1.70xP10
Oats	06-24	.82	3.6	$\hat{Y}$= 61.90 − 4.45xP09 − 0.86xT14 − 6.65xP10 − 0.34xT15 + 0.49xT10 − 2.95xP21 + 1.82xP17 − 2.34xP12
	06-17	.69	4.5	$\hat{Y}$= 73.08 − 4.97xP09 − 0.89xT14 − 4.14xP10 − 0.38xT15 + 0.31xT10
GRATIOT				
Corn	08-32	.52	6.7	$\hat{Y}$= −83.15 + 5.90xP16 + 5.21xP21 + 6.02xP22 + 0.99xT20
	08-24	(same as full-season)		
Dry Beans (cwt.)	08-32	.61	1.5	$\hat{Y}$= 14.45 − 2.34xP19 − 0.22xT25 + 0.57xP20 + 1.11xP24 + 1.09xP11
	08-24	.42	1.8	$\hat{Y}$= − 0.77 − 1.31xP19 + 0.84xP20 + 1.18xP24
Soybeans	08-32	.71	1.3	$\hat{Y}$= −19.14 − 0.19xT16 − 0.19xT21 − 1.21xP32 + 0.24xT22 + 0.70xP23
	08-24	.43	1.7	$\hat{Y}$= 1.39 + 1.15xP16 + 1.13xP20 + 0.15xT08 − 0.16xT17
Oats	06-24	.41	5.2	$\hat{Y}$= 90.37 − 0.40x(T16+T17) − 0.55xT14
	06-17	.41	5.2	$\hat{Y}$= 81.24 − 0.65xT17 − 0.55xT14

Note: 1) P= precipitation; T=temperature; subscript nn denotes week
2) These equations predict the deviation from trend; adding trend value for a given year gives the predicted yield for that year

Given the time distribution of significant variables and the differences in the results from the counties, it is difficult to specify with any accuracy a specific group of weeks or block of time when either temperature or precipitation can be judged consistently important. For corn, adequate precipitation in late July and early August is important in Lenawee County, and in late July in Gratiot County. Oats appear to require fairly cool weather in June. In some cases an apparent lag exists between Lenawee County and Gratiot County which is approximately 120 miles to the north, but this is not consistent.

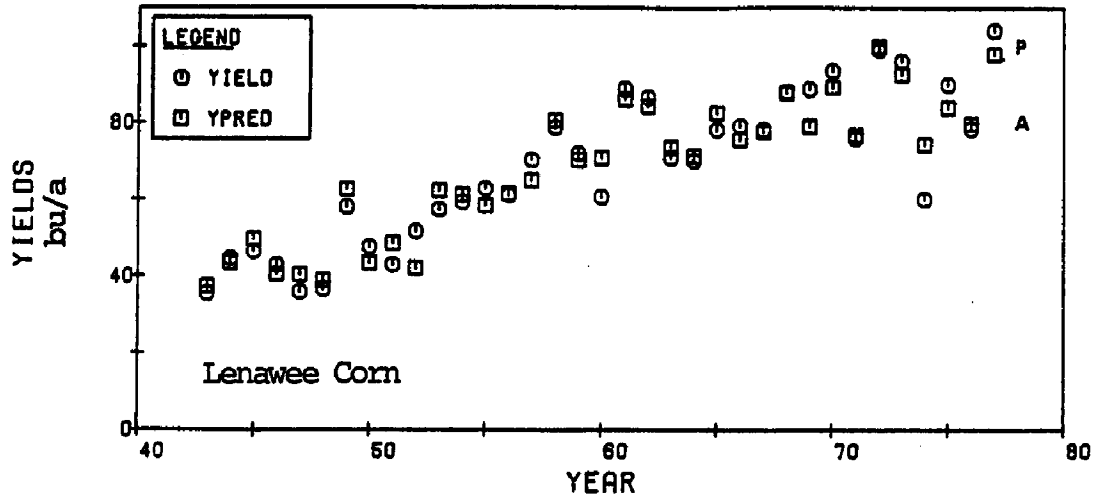
Actual yields and yields predicted from regression models based on weekly data are shown in Figure 10.

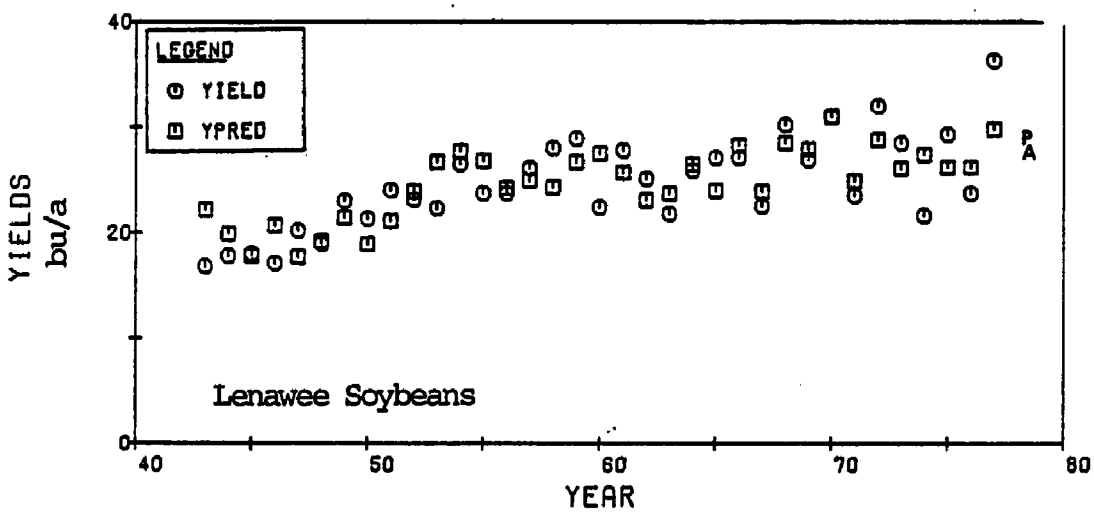
MODIFICATION OF PRECIPITATION DATA

Prediction models based upon weekly data are susceptible to inflation if a predictor week should have heavy rainfall. Two methods of avoiding such inflation were tested. The first method removes excess daily rainfall as was done with monthly-based models. The second uses as a constraint a specified level of gamma distribution for weekly rainfall.

NON-EXCESS PRECIPITATION

Using the first method, 1978 Lenawee County corn yield was predicted with the removal of all precipitation in excess of one inch and two inches in any single calendar day. The prediction based on actual precipitation was 98.7 bu/a, while actual yield was 76.1 bu/a. Removal of all precipitation in excess of one inch in a





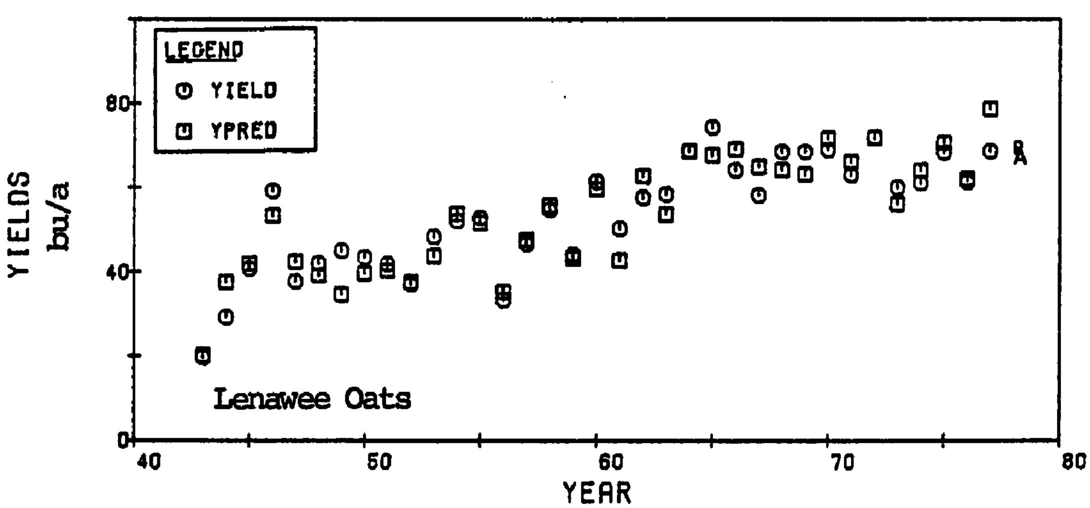
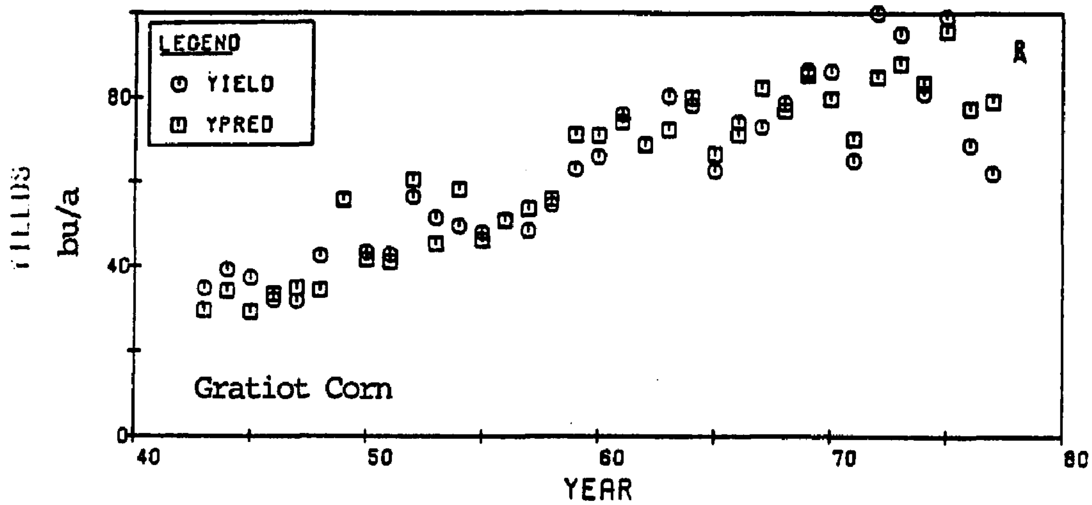


Figure 10. Actual and Predicted Yields, Weekly Data, 1943-1977 plus 1978



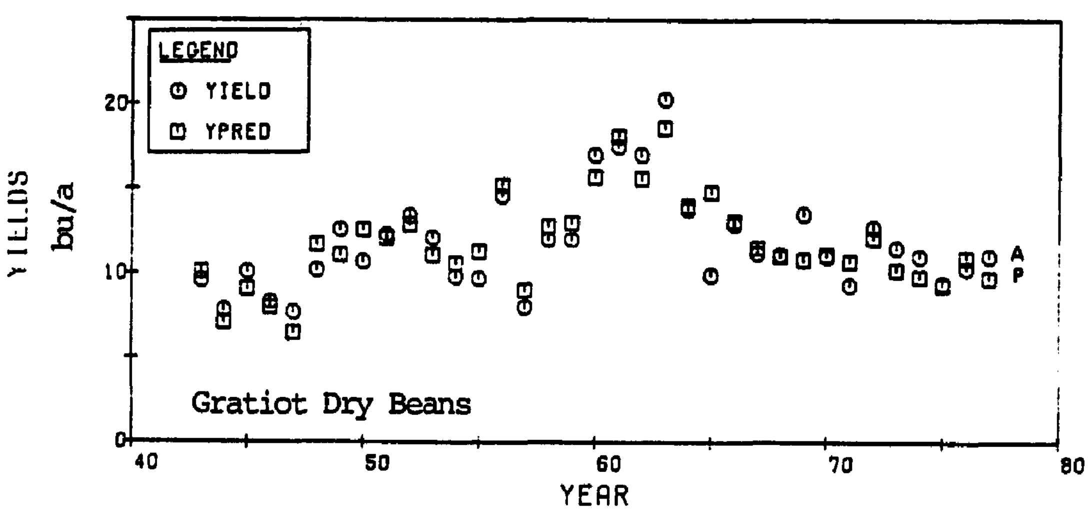
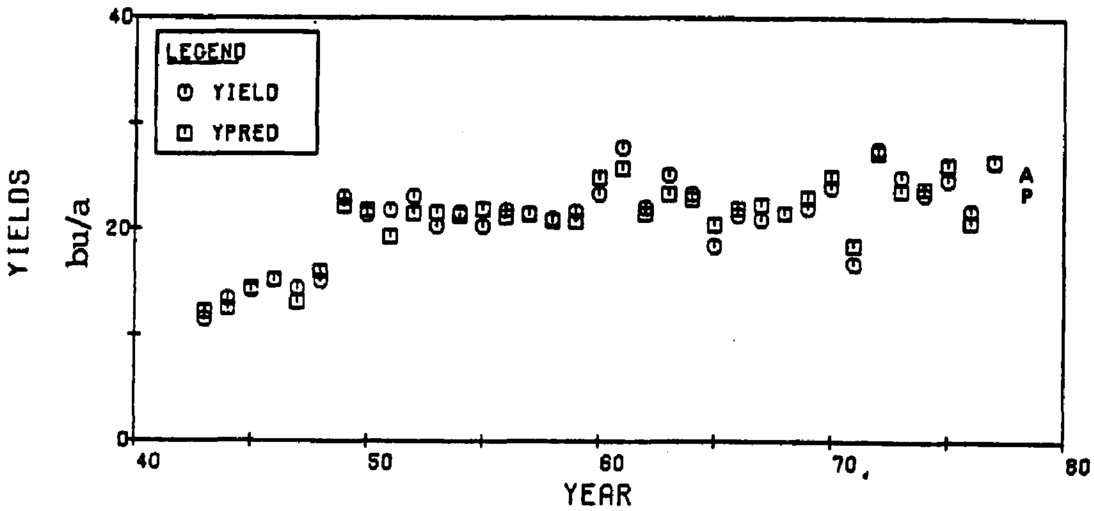


Figure 10. (Continued)



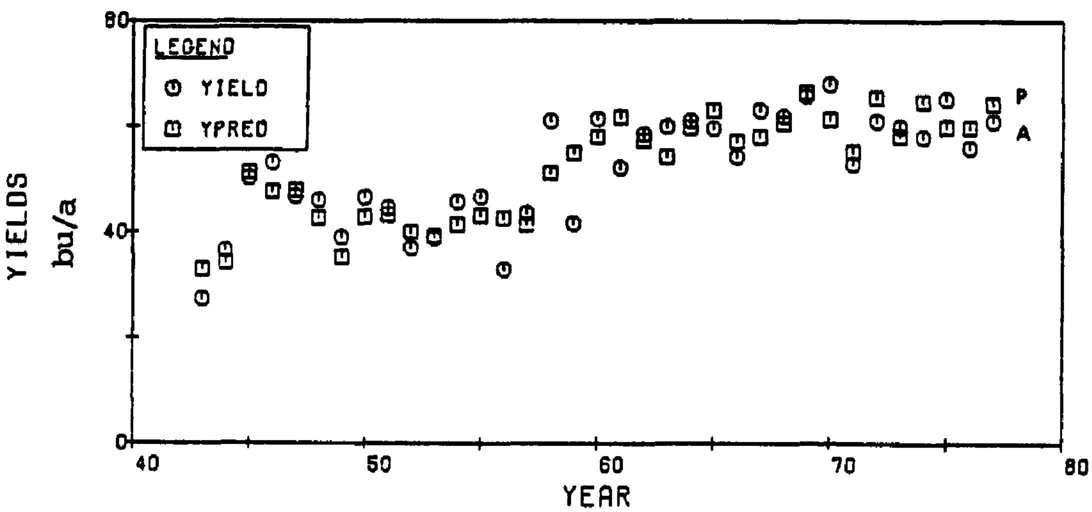


Figure 10. (Continued)

day resulted in a prediction of 83.5 bu/a, while removing all above 2 inches gave a predicted yield of 92.0 bu/a.

GAMMA DISTRIBUTION OF RAINFALL

The gamma distribution for Lenawee and Gratiot weekly precipitation was obtained from the Michigan Department of Agriculture/Michigan Weather Service (Table 12). Actual precipitation for all predictor weeks which had predictions outside two s.e.'s from actual yields for the 1943-1977 period of the study plus the 1978 data were checked against the .90 level of the gamma distribution. This revealed only two cases in addition to the 1978 Lenawee corn case. For that case, the .90 gamma level (1.65 in.) was substituted for the 23d week actual precipitation (2.78 in.), and the .90 gamma level (2.14 in.) was substituted for the actual (2.15 in.) rainfall for the 29th week. The resulting yield prediction of 88.7 bushels was closer than the uncorrected version to a reasonable figure.

The Lenawee soybean model showed an excess of .01 inches in the 29th week for 1978. This had an effect on yield prediction of only .01 bushels. In 1944 the 10th and 17th weeks in the Lenawee oat model had precipitation above the .90 gamma level. This resulted in an adjustment for the oat yield prediction from 37.5 bushels downward to 31.3 bushels, which was much closer to the 29.2 bushel actual yield. In all other cases predictor week precipitation was below the .90 gamma level, or adjusting the predictor variables would have resulted in a larger difference between actual and predicted yields.

Table 12. Gamma distribution of weekly precipitation, .90 and .95, Adrian and Alma, 1929-77

		Adrian, Lenawee Co.			Alma, Gratiot Co.					Adrian, Lenawee Co.			Alma, Gratiot Co.		
Week	ends	mean precip	.90	.95	mean precip	.90	.95	Week	ends	mean precip	.90	.95	mean precip	.90	.95
1	3/07	.57	1.29	1.69	.57	1.28	1.70	19	7/11	.69	1.53	2.06	.58	1.18	1.54
2	3/14	.55	1.27	1.70	.39	.80	1.03	20	7/18	.82	1.77	2.34	.80	1.70	2.25
3	3/21	.58	1.20	1.51	.46	.97	1.25	21	7/25	.86	1.95	2.62	.51	1.11	1.49
4	3/28	.75	1.62	2.10	.58	1.14	1.44	22	8/01	.65	1.42	1.86	.71	1.52	1.96
5	4/04	.92	1.83	2.31	.62	1.30	1.66	23	8/08	.78	1.65	2.15	1.02	2.17	2.84
6	4/11	.68	1.48	1.90	.59	1.17	1.47	24	8/15	.56	1.15	1.47	.83	1.61	2.06
7	4/18	.80	1.60	2.05	.61	1.34	1.74	25	8/22	.84	1.71	2.19	.88	1.81	2.37
8	4/25	.97	2.09	2.70	.77	1.74	2.33	26	8/29	.77	1.51	2.11	.94	1.93	2.65
9	5/02	.81	1.82	2.39	.89	1.91	2.51	27	9/05	.78	1.67	2.21	.90	2.00	2.69
10	5/09	.76	1.56	1.97	.74	1.66	2.23	28	9/12	.65	1.38	1.81	.84	1.77	2.31
11	5/16	.97	2.16	2.84	.75	1.64	2.15	29	9/19	.96	2.14	2.95	.95	2.04	2.67
12	5/23	.78	1.65	2.15	.62	1.33	1.72	30	9/26	.60	1.35	1.76	.83	1.75	2.24
13	5/30	.70	1.56	2.03	.70	1.61	2.12	31	10/03	.77	1.61	2.13	.71	1.62	2.19
14	6/06	.87	1.74	2.18	.73	1.58	2.04	32	10/10	.80	1.73	2.29	.77	1.54	2.00
15	6/13	.81	1.76	2.27	.77	1.71	2.26	33	10/17	.73	1.52	2.12	.66	1.35	1.81
16	6/20	.97	2.31	3.11	.77	1.81	2.40	34	10/24	.73	1.63	2.18	.60	1.46	1.98
17	6/27	1.00	2.17	2.85	.85	1.75	2.25	35	10/31	.43	.87	1.14	.53	1.10	1.44
18	7/04	.94	2.05	2.66	.73	1.64	2.17								

Data Courtesy of Michigan Weather Service

COMPARISON OF RAINFALL
LIMITATION METHODS

Use of the .90 gamma level as a maximum for precipitation in the 1978 Lenawee corn case gave a yield prediction of 88.7 bu/a, compared with 98.7 bushels for actual precipitation and an actual yield of 76.1 bushels. For the 23d week, net weekly precipitation after removal of rainfall in excess of one inch in any day is equivalent to the .77 gamma level, and for a 2-inch excess, the .94 gamma level.

ANALYSIS OF OUTLYING YIELDS

Why were predictions farther from actual yield values in certain years? To determine this, years with weekly-based predictions greater than two standard errors from actual yields were examined in search of information which might explain the source of difference and thus provide a basis of judgment to apply in future predictions.

Lenawee corn yields in 1974, while predicted to be well below trend, were much lower than predicted. Soybean yields that year were also lower than predicted. A very dry mid and later summer, combined with an early killing frost, was the probable cause.

Lenawee soybeans in 1943 fell well below prediction. Normal weather in July and August favored a good crop and a good prediction. However, a cold and wet April and May had delayed planting, and a very cool September limited the maturing process. A moist August of 1977, not included in the predictor variables, boosted soybean yields well above predictions for that year.

In 1944, Lenawee oat yields were favored by good weather in the last half of May and most of June; this period contained four of the eight predictor variables as shown in Table 4.7. However, cold, wet weather in April and early May delayed planting, and dry weather from June 23 on may have hampered grain filling. Adjustment of precipitation in the 10th and 17th weeks to the .90 gamma level revised the yield prediction downward from 37.5 bushels to 31.3 bu/a, which was closer to the actual yield of 29.2 bushels. In 1977, a cool (averaging 4.6°F below normal) and moist June gave oat yields higher than indicated by the predictor variables. This was, however, consistent with negative temperature correlation coefficients through June. Negative precipitation correlations during May are also consistent with the 1944 case discussed above.

Gratiot corn in 1977 gave yields considerably lower than predicted. While rainfall was more than ample, which increased the yield prediction, cold temperatures late in the season appear to have inhibited the maturation process. August averaged 3.2°F colder than normal, with maximum daily temperatures below 80°F for 18 days of the month, and minima below 50°F for 12 days.

THE PHENOLOGICAL ADJUSTMENT APPROACH

Plant growth responds not to calendar dates but to actual environmental conditions. Primary control on plant growth is considered to be accumulated heat units above a specified threshold value. Therefore climatic data were adjusted so that values of weekly independent climatic variables regressed against Lenawee corn yield deviations from trend were conditions which the plant faced at certain phenological stages based on weekly cumulative 86/50 growing degree days from the beginning of week 9 (April 26) rather than on elapsed calendar time.

Comparison of real-time vs. phenologically adjusted weekly climate data for Lenawee County crops is shown in Table 13. In comparison, R^2 values were higher at each step for real-time data, significance levels were smaller and more variables were allowed into the model at the 5% level, and standard errors of estimate were smaller. These results suggest that this appraoch was not a fruitful direction of inquiry in this particular study.

WEEKLY VS. MONTHLY REGRESSIONS

As a basis for comparison, Lenawee corn yields were regressed against monthly weather data in the same way as the weekly analysis, with both constrained to the 5% level of significance for all variables entering the equation. The R^2 value of the month-based regression was .14, allowing only August precipitation to enter the equation, in contrast to an R^2 of .71 with 6 variables at the weekly level. For comparison, the first variable alone in the week-based analysis gave an R^2 of .30. Standard error for the month-based regression was 8.7 bushels, versus 5.5 at the weekly level.

Constraints in the monthly analysis reported in the first part of this chapter were much less rigorous than the 5%

Table 13. Yield Regression Statistics, Real-Time vs. Phenologically Adjusted Weekly Climatic Data, Lenawee County, 1943-77

			Real-Time				Phenologically Adjusted			
Crop	Weeks	Var#	Var.	R^2	Sig.	s.d.	Var.	R^2	Sig.	s.d.
Corn	9-30	1	P23	.30	.001	7.9	P23	.18	.011	8.5
		2	P29	.43	.012	7.2	P11	.27	.062	8.2
		3	P22	.51	.026	6.8	---			
		4	T16	.56	.079	6.5				
Soybeans	9-30	1	P29	.22	.005	2.6	T20	.11	.051	2.8
		2	T30	.35	.018	2.4	P26	.22	.046	2.7
		3	T20	.44	.029	2.3	T13	.30	.062	2.5
		4	T16	.52	.041	2.2	P15	.38	.054	2.4
		5	P26	.58	.040	2.0	T14	.46	.050	2.3
		6	---				P29	.53	.058	2.2
							1st 6 only used			
Oats	9-24	1	P09	.22	.005	6.7	P12	.22	.004	6.7
		2	T14	.43	.001	5.8	P09	.36	.013	6.2
		3	P10	.55	.007	5.2	P10	.47	.014	5.7
		4	T15	.64	.015	4.8	T14	.54	.048	5.4
		5	T10	.69	.032	4.5	P21	.60	.035	5.1
		6	P21	.74	.027	4.2	---			
		7	P17	.79	.025	3.9				
		8	P12	.82	.025	3.6				
			1st 8 only used							

Note: Last significance level of 5% or less is underlined

Variables given by week number; T: temperature
P: precipitation

Sig.: significance level

s.d.: standard deviation

*: no variables below 5%

significance level used in the weekly analysis. In order to attain reasonable R^2 values, variables were allowed to enter the month-based predictive equations up to a significance level of nearly .15. Ranges in R^2 values with the weekly analysis were from .41 to .82, compared with .15 to .56 for the monthly analysis. Standard errors of predicted value with the monthly analysis were from 1.8 to 6.96 bu/a. The full-season weekly model gave standard errors of 1.3 to 6.7 bu/a, while the mid-season models ranged from 1.7 to 7.4 bu/a standard error.

INTERCORRELATION OF INDEPENDENT VARIABLES

In multiple regression analysis, it is preferable that the relationships among the independent variables are linear and additive. A small amount of intercorrelation does not cause much difficulty, but with extreme collinearity, in the 0.8 to 1.0 range, the regression coefficients may be less stable in indicating relative importance of the different variables. In such a case, two possible solutions are: (a) create a single new variable from the highly correlated variables to use in place of them, or (b) use only one of the highly intercorrelated variables (Kim and Kohout, 1975).

In the weekly-based analysis using only temperature and precipitation, intercorrelation was not a factor. The highest intercorrelation was +0.62, between 12th week precipitation and 24th week temperature, with no suggestion of causality. All others were ±.58 or less, with no pattern of occurrence.

In the monthly-based analysis we find intercorrelations of .93 to .99 between similar unsquared and squared terms, as might be expected. For example, intercorrelation between temperatures and squared temperatures for specific months in Lenawee County ranged from .95 to .99.

Squared terms were included in the multiple regression analysis to determine if relationships between yields and specific climatic variables were linear or quadratic. The more dominant term was selected by the analysis program. Thus the program followed alternative (b) of Kim and Kohout's solution above. Analyses were also run with unsquared terms only and squared terms only. Runs made with both squared and unsquared terms together gave higher R^2 values and lower standard deviations than when run separately.

LIMITATIONS

CATASTROPHIC EVENTS

A yield model which depends on long-term relationships of yields to recorded numerical climatic data often suffers from a basic limitation. Often the specific factor which affects yield is a catastrophic event which does not appear in the data or is diluted by the number of observations over a long period. Some of the events which depress yields may slip through the statistical process undetected. Some effects which depress yield may be secondary weather-related causes, such as a pest or disease outbreak. Such events may be a particular problem when applying the predictive equation to a particular year, or predicting yield by a technique which does not take into consideration such events.

AREAL VARIABILITY

Another limitation lies in the areal variability of weather events such as convective precipitation. Nearby fields, whether in the same county or the same township or even the same section, may have different soil moisture regimes due simply to the apparently capricious movement of one or several storms. A 20-year study of precipitation with 22 recording rain gages on two small stream watersheds in south central Lower Michigan demonstrates that one observation station in the center of a county is not necessarily representative of precipitation available for crop growth in the entire county (Eichmeier, Wheaton, and Kidder, 1959; Wheaton, Kidder, and Eichmeier, 1964; and Mueller, Merva, and Strommen, 1968).

On a larger scale, area variability of crop yields is shown by the following examples. Oat yields in Lenawee County in 1946 were 18.3 bu/a above the trend line, while in Gladwin County in the same year they were 17.4 bu/a below trend. In 1977 Lenawee County corn yield was 16.3 bu/a above trend, while the Gladwin yield was 13.5 bu/a below the trend line.

On a state-wide scale, climatic commentaries in monthly and annual climate and/or crop data reports are often contradictory to specific local or county conditions. The local departures from "normals" may provide more accurate clues than such summary comments.

CHAPTER V

SUMMARY AND CONCLUSIONS

The purpose of this study is to develop a better understanding of the relationships between specific climatic variables and on-farm yields of major field crops in Lower Michigan.

SUMMARY

THE STUDY PROCESS

CLIMATE

Climate records were obtained for selected cooperative observer stations. These stations were located along a south-to-north transect up the interior of the peninsula. Reasonably complete records were obtained from Adrian in Lenawee County and Alma in Gratiot County for 1892 through 1977 and for 1926-1977 for Gladwin in Gladwin County.

Temperature and precipitation were selected as the primary climatic variables. Missing temperature data were estimated by linear regressions against nearby stations. Precipitation was estimated by isopleth analysis. The initial analysis used data on a monthly scale.

Secondary climate variables were developed for the monthly analysis. To allow for loss of crop-available water from surface runoff due to intense convection storms, two alternate precipitation variables were derived. Two levels of excess precipitation, or that greater than one inch and two inches in a calendar day, were removed, leaving these non-excess precipitation values as alternate sets of precipitation data.

A cumulative moisture variable was derived from a soil bank-balance approach. This began the crop season April 1st with a full soil profile, adding monthly precipitation and subtracting potential evapotranspiration for each month. Potential evapotranspiration was calculated by the Thornthwaite method, based on temperature and day-length index.

The Moisture Stress Index developed above was recoded to a Moisture Availability Index by adding 34 to each MSI, to make all data values positive.

Later in the research porcess the analysis moved to the weekly scale. Records for weekly precipitation and growing degree days were obtained for the Adrian and Alma station for the 1943-47 period. These records covered the 35 weeks from March 1 through October 31. Temperature data were calculated from the total weekly base of 40°F growing degree day data. The final weekly model included only temperature and precipitation.

CROPS

Records of corn and oat yields were obtained for 1892-1977 for Lenawee and Gratiot Counties, and for 1926-1977 for Gladwin County. Dry bean records were available for Gratiot County for 1895 through 1977. Soybean data were available for Lenawee and Gratiot Counties for 1942-1977.

RELATIONSHIPS

Over the period of the study yields have increased markedly, especially from 1940 to 1970. Much of this increase is due to development of improved technology and its application as management practices. Inspection of climatic data does not display the same secular trend which is apparent in yield data. Therefore removal of this long-term trend from yield data allows our analysis to concentrate on short-term variations.

Trend removal is accomplished by fitting appropriate regression lines to segments of the actual yield data in order to determine trend, then using the resulting variations about trend as the dependent yield variable in our multiple regression analysis. After analysis the annual values of the trend lines are added back into the predicted departures from the lines to provide a predicted yield.

A stepwise multiple regression was used, with de-trended crop yield as the dependent variable. Two separate analyses were made, one with monthly-scale climate data and one with weekly data. For both, independent variables included temperature and precipitation. For the monthly analysis, variables also included a moisture availability index for each of the growing season months of April through September, and the squares of each of the three sets of terms. For oats, the September data set was excluded, since the crop is already harvested.

RESULTS

MONTHLY ANALYSIS

The most important variables for corn, soybeans, and dry beans in the monthly analysis were July and August precipitation, with a positive relationship. September temperatures were also important for corn in all three counties. For oats, June temperatures were the most significant variable in all cases, with a negative relationship. July temperatures entered the equation for Lenawee and Gladwin oats; April and May temperatures for Gratiot and Gladwin oats; and May temperatures for Lenawee oats. June precipitation also appeared for Gratiot and Gladwin oats.

The Moisture Availability Index, while appearing in some cases, was of relatively little importance. Removal of daily rainfall in excess of one inch from the analysis did not improve the results, except for Gratiot soybeans. Removal of rainfall over two inches also did not improve the analysis more than marginally.

Stepwise multiple regression analysis was constrained to a significance level of approximately .15. For the detrended yields, R^2 values for monthly regression models ranged from .21 for Gratiot dry beans, with a standard deviation of 1.87 cwt/a (270 kg/ha) to .56 for Lenawee soybeans, with a s.d. of 2.14 bu/a (412 kg/ha).

WEEKLY ANALYSIS

A multiple regression analysis was applied to detrended crop yields for Lenawee and Gratiot Counties for the years 1943-1977. Independent variables were mean weekly temperatures and total weekly precipitation.

Corn yield was positively related to precipitation in late July and early August. Soybeans appeared to be helped by timely rains in July, August, and September. July and August precipitation showed a positive relation to dry bean yields. Oat yields were negatively related to June temperatures.

While restricting the number of variables by requiring a 5% significance level for inclusion, R^2 values were higher than those obtained by the monthly analysis. Weekly-based R^2 values ranged from .41 for Gratiot oats, with a standard deviation of 5.2 bu/a (197 kg/ha), to .82, with a s.d. of 3.6 bu/a (137 kg/ha) for Lenawee oats.

CONCLUSIONS

RELATIONSHIPS

Specific climate factors do explain a significant portion of the variation in yields about a long-term trend line. Adequate precipitation in July and August is most important for corn, soybeans, and dry beans. A cool June is most important for oats.

Analysis based on weekly rather than monthly data shows promise; it allows predictive models which provide more accurate estimates of crop yields for the current season. Accuracy in this case means a higher significance level and smaller error of the predicted value. A truncated mid- to late-season weekly model, while in most cases not as accurate as the full-season version, may be useful in developing early estimates of yields for the current year.

LIMITATIONS

CATASTROPHIC EVENTS

A yield model which depends on long-term relationships of yields to recorded numerical climatic data suffers from a primary limitation. Often the specific factor which affects yield is a catastrophic event which does not appear in the data or is diluted by the number of observations over a long period. Other, non-climatic problems may also occur, as well as those indirectly related to climate.

An example of the former sometimes occurs in dry beans. A growing season may have optimum conditions for maximizing yields, except for a 3-inch (7.6 cm) thunderstorm on August 21. The latter may be the invasion of southern corn leaf blight or army worms.

AREAL VARIABILITY

Another limitation lies in the areal variability of weather events, such as convective precipitation. Nearby fields may have different soil moisture regimes due simply to the apparently capricious behavior of one or several storms.

MONTHLY VS. WEEKLY ANALYSES

While monthly climate records are more commonly available, anslysis based on weekly data appears to have advantages. In this study, higher significance levels could be used with a weekly-based analysis, with a larger part of the variability of the dependent variable accounted for and a smaller standard deviation. Correlations between independent variables and the dependent variable, while not statistically acceptable at high levels of significance, may at the weekly level more closely indicate critical stages in plant development if used with caution.

Regression models become more sensitive to critical stages of plant growth at the weekly scale than with monthly data. They are also more sensitive to anomalous events in predictor variables, such as excessive precipitation in a predictor week. The use of constraints on the maximum weekly precipitation figure allowed in the predictive equation may help limit this source of error.

SUGGESTIONS FOR FURTHER STUDY

A researcher would be disappointed if the product of his labors, particularly in a field so closely related to mankind's needs as the production of food, were to gather dust on a shelf. One would hope that those following would find benefit in standing on his shoulders in order to see farther, and more clearly and quickly.

SECONDARY INDEPENDENT VARIABLES

Use of a specific moisture availability variable was not particularly successful in this study. Formulated in a different manner it could be more useful.

Some studies have used amount of nitrogen applied to corn as a proxy variable for technological trend. Some caution is needed in this, as between 1970 and 1976 change from the previous year in the amount of total nitrogen used in Michigan was opposite in sign to change in state average corn yields in five years out of six (Michigan Department of Agriculture, 1972-78).

While the weekly-based analysis using only temperature and precipitation variables is an improvement over the more complex monthly analysis, application of carefully developed secondary variables may improve it. The use of squared terms in this analysis showed little improvement.

REMOVAL OF TREND

The use of detrended yields such as in this analysis may prove useful in determining the nature of short-term variations. While the use of piecewise regressions to determine trends appeared preferable to higher-order curve-fitting techniques, it is suggested that the application of cubic splines may give a more accurate means of removing trend.

PHENOLOGICAL STAGES

The growing plant responds to climatic conditions and the existing weather, rather than to the calendar. Yields may be influenced by the weather existing at certain vulnerable stages of development. Thus, where reasonably accurate and reliable phenological and weather information is available, better results may be obtained by relating weather conditions to growth stages rather than to calendar months or weeks. This is especially true under conditions of earlier plantings in recent years, and of increased climatic variability. While the attempts made in this study to adjust weather data to plant development were not successful, it is suggested that this subject should be studied further.

PATTERN ANALYSIS

Where patterns exist, they may ordinarily be expected to continue and repeat. Determination of the nature of past climatic patterns could therefore be of value in estimating the future environment for plant growth.

Fourier analysis and autocovariance techniques were applied to the data in this study in an attempt to determine patterns which exist in climate and/or yield data. Length of record proved to be too short for adequate analysis.

CAVEATS

One must be constantly aware of variability and inconsistency in the records. For example, the summer may have been dry over the entire state, sharply decreasing state corn yields, but a part of one county may have had one or two well-timed heavy rains and thus high corn yields. Narrative statewide summaries in the weather records were often contradictory to local conditions. Also, a given weather observation station may have been moved one or several times, with the various location microclimates affecting the spatial and temporal validity of the record.

Correlational and regression studies must be used with adequate levels of knowledge and judgment. As an example, a multiple regression early in this study indicated a strong relationship between Lenawee County oat yields and September temperatures. A moment's reflection reminds us that oats are harvested by the end of August, ruling out any causal relationship.

THE END AND A BEGINNING

The author sincerely hopes that other researchers will continue the study of crop-climate relationships in Michigan. The current state of the art leaves a great opportunity for further development in this field.

LIST OF REFERENCES

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Andersen, A. L. and L. S. Robertson, 1978. The Michigan dry edible bean industry - history. In: Dry bean production - principles and practice. Extension Bulletin E-1251, Michigan Agricultural Experiment Station, August, 1978. p. 1.

Achutuni, Vasuveda R., Amos Eddy, and Sharon K. LeDuc, 1979. Development and testing of technology-weather-phenology related corn yield models for Iowa and Illinois. 13th Conference on Agriculture and Forest Meteorology, American Meteorological Society, Purdue University, April 4-6, 1977. pp. 70-71.

Baier, Wolfgang, 1977a. Crop-weather models and their use in yield assessments. Tech. Note Nr. 151, WMO Nr. 458, World Meteorological Organization. pp. 22-30.

________, 1977b. Analysis of present knowledge of climatic variability as related to Canadian agriculture. Climatic variability in relation to agricultural productivity and practices, 1977 meeting of the Canada Committee on Agrometeorology, Winnipeg, Manitoba, January 11-12, 1977. Research Branch, Canada Department of Agriculture, Ottawa, January, 1977. p. 7.

Bark, L. Dean, 1978. A study of the effects of altering the precipitation pattern on the economy and environment of Kansas. Final report to Kansas Water Resources Board. Department of Physics, Kansas State University, Agricultural Experiment Station, Manhattan, Kansas, October 1, 1978. pp. 39-47, 171-172.

Brown, James M. 1973. Tables and conversions for Microclimatology. General Technical Report NC-8. North Central Forest Experiment Station, St. Paul, Minn., USDA, Forest Service. pp. 16-17.

Bryson, Reid A., 1975. Shooting at a moving target. Crop Productivity--Research Imperatives. Michigan Agricultural Experiment Station and C. F. Kettering Foundation. pp. 109-132.

Butz, E., n.d. Report on the influence of weather and climate on U.S. grain production. United States Department of Agriculture, Washington, D.C. Unpublished; quoted in Thompson, 1975.

Chang Jen-Hu, 1968. Climate and agriculture; an ecological survey. Aldine Publishing Co., Chicago. pp. 149-150.

Clough, M., 1968. Trends and variations in corn yields over the last fifty years. Feed Situation, Economic Research Service, USDA, Fds-222, February, 1968. pp. 28-32.

Dale, Robert F., 1964. Changes in moisture stress days since 1933. Weather and our food supply, CAED Report Nr. 20, Center for Agricultural and Economic Development, Iowa State University, Ames, Iowa. pp. 23-43.

________, 1965. Weather and technology: a critical analysis of their importance to corn yields. Agricultural Science Review, v. 3, Nr. 4, 4th Quarter 1965. pp. 25-31.

________, 1968. The climatology of soil moisture, evaporation, and non-moisture stress days for corn in Iowa. Agricultural Meteorology, v. 5, March, 1968. pp. 111-128.

________, 1977a. An energy-crop growth variable for identifying weather effects upon corn growth and yield. 13th Conference on Agriculture and Forest Meteorology, American Meteorological Society, Purdue University, April 4-6, 1977. pp. 85-86.

________, 1977b. Final report: correlating corn growth and development with weather. Report under NSF Grant ATM 75-10001 A01, Purdue University, West Lafayette, Indiana. pp. 1-15.

Dale, Robert F. and Harry F. Hodges, 1975. Weather and corn yield study for Tippecanoe County, Indiana. Final Report to Director, Environmental Data Service, National Oceanic and Atmospheric Administration.

Denmead, O. T. and R. M. Shaw, 1960. The effects of soil moisture stress at different stages of growth on the development and yield of corn. Agronomy Journal, v. 52, May-June 1960. pp. 272-274.

Edey, S. N., 1977. Freeze probabilities. Climatic variability as related to agricultural productivity and practices, 1977 meeting of the Canada Committee on Agrometeorology, Winnipeg, Manitoba, January 11-12, 1977. Research Branch, Canada Department of Agriculture, Ottawa. January, 1977. Sec. 3.5, pp. 1-7.

Eichmeier, A. H., R. Z. Wheaton, and E. H. Kidder, 1959. Variation in summertime rainfall in south central Michigan. Quarterly Bulletin of the Mich. Agr. Exp. Sta., Michigan State University, East Lansing. v. 41, Nr. 4, May, 1959. pp. 886-888.

Epstein, Edward S., 1977. Federal plan for a National Agricultural Weather Service; a first version. p. 1.

Erdmann, Milton H., 1979. Personal discussions, August, 1979.

Grafius, John E., 1979. Personal conversation, March 7, 1979.

Gross, E. R. and R. H. Rust, 1972. Estimation of corn and soybean yields using multiple curvilinear regression methods. Proceedings of the Soil Science Society of America, v. 36, March-April, 1972. pp. 316-320.

Haigh, Peter H., 1977. Separating the effects of weather and management on crop production. Report on Kettering Foundation Project ST 77-44 through James D. McQuigg, Certified Consulting Meteorologist, Columbia, Mo., November, 1977. 93 pp.

Hill, R. W., D. R. Johnson, and K. H. Ryan, 1979. A model for predicting soybean yields from climatic data. Agronomy Journal, v. 71, Nr. 2, March-April, 1979. pp. 251-256.

Holt, R. F. and D. R. Timmons, 1968. Influence of precipitation, soil water, and plant population interactions on corn grain yields. Agronomy Journal, v. 60, July-August, 1968. pp. 379-381.

Huda, A.K. Samsul and E. C. A. Runge, 1978. Developing and testing models for corn production. Agronomy Abstracts, 70th Annual Meeting, American Society of Agronomy, Chicago, December 3-8, 1978. p. 11.

Katz, Richard W., 1977. Sensitivity analysis of statistical crop-weather models. 13th Conference on Agricultural and Forest Meteorology, American Meteorological Society, Purdue University, April 4-6, 1977. pp. 1-2.

Kim, Jae-On and Frank J. Kohout, 1975. Multiple regression analysis, in Nie, Normal et al., Statistical Package for the Social Sciences, 2d Edition, McGraw-Hill, N.Y., 1975. pp. 320-360.

Lawlor, D. J. and W. C. Liebhart, 1978. The temporal effect of climatic parameters upon corn yield in the Delmarva Peninsula. Agronomy Abstracts, 70th Annual Meeting, American Society of Agronomy, Chicago, December 3-8, 1978. p. 11.

Linvill, Dale E., 1972. Microclimatic radiation and the growth rate of corn. Unpublished Ph.D. thesis, Purdue University, West Lafayette, Indiana, December, 1972.

McCloud, D. S., 1977. Florida field crop yield trends with a changing climate. Proceedings, Soil and Crop Society of Florida, v. 36. pp. 200-204.

Leeper, R. A., E. C. A. Runge, and W. M. Walker, 1974. Effect of plant-available stored soil moisture on corn yields. II. Variable climatic conditions. Agronomy Journal, v. 66, Nr. 6, November-December, 1974. pp. 798-733.

McKay, G. A. and T. Allsopp, 1977. Climate and climate variability. Climatic variability as related to agricultural productivity and practices, 1977 meeting of the Canada Committee on Agrometeorology, Winnipeg, Manitoba, January 11-12, 1977. Research Branch, Canada Department of Agriculture, Ottawa, January, 1977. Sec. 2.1, pp. 1-10.

McQuigg, James D., 1975. Economic impacts of weather variability. Atmospheric Science Department, University of Missouri-Columbia. August, 1975.

________, 1976. Climatic constraints on food grain production. Paper presented to the World Food Conference of 1976, Ames, Iowa, June 27-July 1, 1976.

Michigan Department of Agriculture. Michigan Crop Report. USDA cooperating. Continued through various state and federal agencies from prior to 1886 to the present.

________, 1972 through 1978. Michigan Agricultural Statistics. Michigan Crop Reporting Service, Michigan Department of Agriculture, Annual Reports released in June or July for previous year.

________, 1979. Michigan Agricultural Statistics. Michigan Agricultural Reporting Service, Michigan Department of Agriculture, July, 1979 and 1979 periodic mail reports.

Mueller, Charles C., George E. Merva, and Norton D. Strommen, 1968. Seasonal variation of topographical effects on precipitation measurements. Quarterly Bulletin of the Mich. Agr. Exp. Sta., Michigan State University, East Lansing, v. 50, Nr. 4, May, 1968. pp. 599-605.

Niell, J. C. and F. A. Huff, 1979. Crop-weather models. 14th Conference on Agricultural and Forest Meteorology, American Meteorological Society, Minneapolis, Minn., April 2-6, 1979. pp. 57-58.

Nelson, William L. and Robert F. Dale, 1977. The influence of record period on the estimates of weather and technology effects on corn yield in multiple regression models. 13th Conference on Agricultural and Forest Meteorology, American Meteorological Society, Purdue University, April 4-6, 1977. pp. 3-4.

________, 1978. A methodology for testing the accuracy of yield predictions from weather-yield regression models for corn (Zea mays). Agronomy Journal, v. 70, September-October, 1978. pp. 734-740.

Palmer, Wayne C. and A. Vaughn Havens, 1958. A graphical technique for determining evapo-transpiration by the Thornthwaite method. Monthly Weather Review, April, 1958. pp. 123-127.

Pfahler, P. L., 1972. Relationship between grain yield and environmental variability in oats. Crop Science, v. 12, March-April, 1972. pp. 254-255.

Ravelo, Andres C. and Wayne L. Decker, 1979. Soybean-weather analysis model. 14th Conference on Agriculture and Forest Meteorology, American Meteorological Society, Minneapolis, Minn., April 2-6, 1979. pp. 72-73.

Robbins, J. S. and C. E. Domingo, 1953. Some effects of severe soil moisture deficits at specific growth stages in corn. Agronomy Journal, v. 45, December, 1953. pp. 618-621.

________, 1956. Moisture deficits in relation to the growth and development of dry beans. Agronomy Journal, v. 48, Nr. 2, February, 1956. pp. 67-70.

Rosenberg, Norman J., 1974. Microclimate: the biological environment. John Wiley and Sons, New York.

Runge, E. C. A., 1968. Effects of rainfall and temperature interactions during the growing season on corn yield. Agronomy Journal, v. 60, Nr. 5, September-October, 1968. pp. 503-507.

________, 1960. The relation between precipitation, temperature, and yield of soybeans on the Agronomy South Farm, Urbana, Illinois. Agronomy Journal, v. 52, Nr. 5, May, 1960. pp. 245-247.

Schaal, Lawrence A. and Byron O. Blair, 1968. The temperature factor in corn production in Tippecanoe County, Indiana. Proceedings of the Indiana Academy of Science of 1967, v. 77, 1968. pp. 389-394.

Schneider, I. F. and A. E. Erickson, n.d. Water-holding capacity and infiltration rates of soils in Michigan (map). Data from Michigan Agricultural Experiment Station Project 413, Soil Science Department, Michigan State University. Date estimated after 1954.

Seeley, Dewey Alsdorf, 1917. The Climate of Michigan and its Relation to Agriculture. Unpublished M.S. thesis, Michigan Agricultural College.

Smucker, A. J. M., D. L. Mokma, and D. E. Linvill, 1978. Environmental requirements and stresses. Dry bean production--principles and practices, Ext. Bul. E-1251, Michigan Agricultural Experiment Station, August, 1978. pp. 59-60.

Steyaert, L. T., 1977. Quality of United States wheat, corn, and soybean crop statistics. University of Missouri, Columbia. Reported in Nelson and Dale, 1978.

Thompson, L. M., 1962. Trends in soybean production and their relation to weather. Soybean Digest, v. 22, Nr. 11, September, 1962. pp. 26-28.

________, 1963. Weather and technology in the production of corn and soybeans. CAED Report Nr. 17, Center for Agricultural and Economic Development, Iowa State University, Ames, Iowa.

________, 1969a. Weather and technology in the production of wheat in the United States. Journal of Soil and Water Conservation, v. 24,. pp. 219-244.

________, 1969b. Weather and technology in the production of corn in the U.S. Corn Belt. Agronomy Journal, v. 61, January-February, 1969. pp. 453-456.

________, 1970. Weather and technology in the production of soybeans in the central United States. Agronomy Journal, v. 62, March-April, 1970. pp. 232-236.

________, 1975. Weather variability, climatic change, and grain production. Science, v. 188, May 9, 1975. pp. 535-541.

U.S., National Oceanic and Atmospheric Administration, Environmental Data and Information Service. Climatological Data.

U.S. Department of Agriculture, Soil Conservation Service. Soil Survey Maps and Interpretation. Special Advanced Report. USDA-SCS in cooperation with the Michigan Agricultural Experiment Station and the Gratiot County Board of Commissioners, 1976.

U.S. Department of Agriculture, Soil Conservation Service. Soil Survey, Gladwin County, Michigan, March, 1972.

U.S. Department of Agriculture, Soil Conservation Service. Soil Survey, Lenawee County, Michigan, Series 1947, Nr. 10, August, 1961.

Weatherwax, Paul, 1923. The Story of the Maize Plant. University of Chicago Press, Chicago, Illinois. p. 12.

Wheaton, R. Z., E. H. Kidder, and A. H. Eichmeier, 1964. Variations in summertime rainfall. Transactions of the American Society of Agricultural Engineers, v. 7, Nr. 2, 1964. pp. 114-115.

Wright, Karl T., 1976a. Unpublished graphs and personal discussions, 1976-78.

________, 1976b. Dry edible bean production trends: world, U.S., and Michigan. Staff paper 76-67, Department of Agricultural Economics, Michigan State University. December, 1976.

APPENDIX

Table A-1. Lenawee County Corn Yields, Actual and Predicted

Year	Actual Yield	Yield Trend	Pred.* Yield
1892	22.2	31.7	25.3
1893	20.5	31.8	23.4
1894	18.0	31.9	26.1
1895	29.0	32.0	28.4
1896	36.0	32.1	37.2
1897	32.0	32.2	30.5
1898	35.0	32.3	36.6
1899	41.0	32.5	35.8
1900	44.0	32.6	37.9
1901	32.0	32.7	27.9
1902	33.0	32.8	31.1
1903	37.0	32.9	38.7
1904	38.0	33.0	38.9
1905	36.0	33.1	33.2
1906	39.0	33.2	37.5
1907	31.0	33.3	34.5
1908	30.0	33.4	33.0
1909	36.0	33.5	29.7
1910	37.0	33.6	36.9
1911	37.0	33.7	39.6
1912	38.0	33.8	40.5
1913	30.0	34.0	34.7
1914	36.0	34.1	32.9
1915	33.0	34.2	40.9
1916	20.0	34.3	25.9
1917	32.0	34.4	35.1
1918	19.0	34.5	23.2
1919	37.0	34.6	24.1
1920	47.0	34.7	42.1
1921	43.0	34.8	41.7
1922	39.0	34.9	38.0
1923	40.0	35.0	29.8
1924	29.0	35.1	30.0
1925	47.0	35.2	40.3
1926	45.0	35.3	37.8
1927	40.0	35.5	40.3
1928	49.0	35.6	36.2
1929	34.0	35.7	27.9
1930	26.0	35.8	21.7
1931	35.0	35.9	37.4
1932	25.0	36.0	36.0
1933	31.0	36.1	40.5
1934	24.0	36.2	28.6
1935	34.0	36.3	36.3

Year	Actual Yield	Yield Trend	Pred.* Yield	Pred.# Yield
1936	34.0	36.4	34.2	
1937	31.0	36.5	31.3	
1938	43.0	36.6	41.6	
1939	41.0	36.7	36.7	
1940	34.0	37.8	34.5	
1941	39.0	38.0	35.6	
1942	52.0	39.7	47.4	
1943	35.5	41.4	34.4	37.3
1944	44.5	43.1	38.4	43.4
1945	46.4	44.8	42.5	49.6
1946	42.8	46.6	40.5	40.4
1947	35.8	48.3	45.4	40.3
1948	36.5	50.0	47.8	38.8
1949	58.0	51.7	46.1	62.6
1950	47.6	53.4	57.9	43.4
1951	42.9	55.1	49.4	48.6
1952	51.6	56.8	55.7	42.0
1953	57.4	58.6	57.7	62.3
1954	59.3	60.3	60.8	61.2
1955	62.8	62.0	62.5	58.5
1956	61.1	63.7	60.2	61.5
1957	70.3	65.4	67.3	65.0
1958	78.8	67.1	75.3	80.7
1959	72.0	68.8	78.7	70.4
1960	60.7	70.6	73.2	70.9
1961	88.9	72.3	79.6	86.3
1962	86.7	74.0	79.1	84.4
1963	70.8	75.7	73.3	73.5
1964	70.0	77.4	83.7	71.2
1965	78.1	79.1	84.5	82.5
1966	79.0	80.8	80.1	75.5
1967	78.0	82.6	82.2	77.5
1968	87.9	84.3	84.7	87.8
1969	88.7	86.9	83.0	78.9
1970	93.4	87.0	84.7	89.3
1971	76.0	87.1	80.5	76.8
1972	99.0	87.2	96.1	99.9
1973	96.0	87.3	87.2	92.7
1974	60.0	87.4	77.9	74.3
1975	90.0	87.5	90.0	84.0
1976	78.4	87.5	80.1	79.7
1977	104.0	87.6	91.7	97.8
1978	76.1	87.7	86.9	88.7[a]
1979		87.8		90.6[b]

*Monthly climate data #Weekly climate data a) .90 gamma b) truncated model

Table A-3. Lenawee County Soybean Yields, Actual and Predicted

Year	Actual Yield	Yield Trend	Pred.* Yield	Pred.# Yield	Year	Actual Yield	Yield Trend	Pred.* Yield	Pred.# Yield
1942	22.8	17.8	22.7		1961	27.8	26.0	28.9	25.7
1943	16.8	18.3	19.4	22.2	1962	25.1	26.1	25.6	23.1
1944	17,8	18.8	16.0	19.9	1963	21.8	26.3	23.4	23.7
1945	18.0	19.3	19.3	17.8	1964	25.9	26.5	29.9	26.5
1946	17.1	19.8	17.6	20.7	1965	27.1	26.6	28.0	24.0
1947	20.2	20.3	18.6	17.7	1966	27.1	26.8	27.0	28.3
1948	18.9	20.8	20.2	19.2	1967	22.5	26.9	25.1	23.9
1949	23.0	21.3	21.0	21.4	1968	30.2	27.1	28.6	28.5
1950	21.3	21.8	21.8	18.9	1969	26.9	27.3	26.2	27.9
1951	24.0	22.3	24.0	21.1	1970	31.0	27.4	28.1	31.0
1952	23.1	22.9	22.0	23.9	1971	23.5	27.6	22.4	24.9
1953	22.3	23.4	21.3	26.7	1972	32.0	27.8	29.6	28.8
1954	26.5	23.9	22.2	27.7	1973	28.5	27.9	26.9	26.1
1955	23.7	24.4	25.9	26.8	1974	21.6	28.1	25.2	27.4
1956	23.7	24.9	23.2	24.2	1975	29.3	28.2	29.6	26.2
1957	26.1	25.4	26.7	24.9	1976	23.7	28.4	25.2	26.2
1958	28.0	25.5	28.3	24.3	1977	36.3	28.6	31.7	29.8[a]
1959	28.9	25.6	28.7	26.7	1978	27.1	28.8	26.1	28.4[b]
1960	22.4	25.8	24.8	27.5	1979		29.0		27.9

Table A-4. Gratiot County Soybean Yields, Actual and Predicted

Year	Actual Yield	Yield Trend	Pred.* Yield	Pred.# Yield	Year	Actual Yield	Yield Trend	Pred.* Yield	Pred.# Yield
1942	13.9	12.8	13.1		1961	27.8	22.4	23.6	25.8
1943	11.5	13.2	11.5	12.2	1962	22.1	22.5	22.0	21.5
1944	13.4	13.6	12.2	12.5	1963	25.2	22.5	23.3	23.4
1945	14.2	14.0	13.7	14.4	1964	23.4	22.6	24.1	22.9
1946	15.2	14.4	13.2	15.2	1965	18.5	22.7	21.9	22.5
1947	14.4	14.8	14.3	13.1	1966	21.4	22.8	22.5	22.0
1948	15.1	15.2	14.1	16.0	1967	21.0	22.9	21.7	22.4
1949	23.0	21.4	22.0	22.2	1968	21.6	22.9	21.6	21.6
1950	21.4	21.5	21.1	21.8	1969	22.0	23.0	21.9	23.0
1951	21.8	21.6	21.9	19.3	1970	24.0	23.1	23.6	25.0
1952	23.1	21.7	23.0	21.5	1971	16.8	23.2	22.0	18.5
1953	20.3	21.8	21.1	21.6	1972	27.6	23.3	24.5	27.3
1954	21.6	21.8	19.8	21.3	1973	25.0	23.3	23.5	23.7
1955	20.3	21.9	23.4	21.9	1974	23.4	23.4	24.8	23.9
1956	21.8	22.0	22.0	21.2	1975	24.7	23.5	26.7	26.1
1957	21.5	22.1	21.1	21.4	1976	21.8	23.6	22.4	20.7
1958	21.0	22.2	22.2	20.8	1977	26.5	23.7	26.0	26.5
1959	21.7	22.2	22.9	20.8	1978	27.4	23.7	21.2	24.0[b]
1960	23.4	22.3	22.7	24.9	1979		23.8		23.5

*Monthly Climate data #Weekly climate data a) .90 gamma b) truncated model

Table A-2. Lenawee County Oat Yields, Actual and Predicted

Year	Actual Yield	Yield Trend	Pred.* Yield
1892	29.1	33.5	25.0
1893	34.0	33.6	29.3
1894	32.5	33.8	24.0
1895	29.6	33.9	35.1
1896	33.1	34.1	31.2
1897	34.3	34.2	37.3
1898	32.4	34.3	36.0
1899	40.0	34.5	35.2
1900	40.0	34.6	38.1
1901	33.0	34.7	36.4
1902	40.0	34.9	39.9
1903	36.0	35.0	41.2
1904	43.0	35.1	42.6
1905	34.0	35.3	36.2
1906	28.0	35.4	36.2
1907	23.0	35.6	40.7
1908	30.0	35.7	32.4
1909	35.0	35.8	34.6
1910	39.0	36.0	36.1
1911	36.0	36.1	31.3
1912	43.0	36.2	38.7
1913	28.0	36.4	31.0
1914	32.0	36.5	28.2
1915	43.0	36.6	46.6
1916	34.0	36.8	40.4
1917	49.3	36.9	41.4
1918	46.0	37.1	42.1
1919	30.9	37.2	26.4
1920	50.4	37.3	39.9
1921	18.0	37.5	28.5
1922	34.0	37.6	30.0
1923	43.0	37.7	36.1
1924	57.0	37.9	44.5
1925	48.0	38.0	41.8
1926	40.0	38.1	43.2
1927	52.0	38.3	45.4
1928	41.0	38.4	43.9
1929	36.0	38.6	35.9
1930	45.0	38.7	36.4
1931	40.0	38.8	37.9
1932	31.0	39.0	36.8
1933	19.0	39.1	28.1
1934	19.0	39.2	31.2
1935	42.0	39.4	41.1

Year	Actual Yield	Yield Trend	Pred.* Yield	Pred.# Yield
1936	36.0	39.5	37.8	
1937	28.0	39.6	35.3	
1938	33.0	39.8	39.4	
1939	41.0	39.9	38.2	
1940	64.0	40.1	38.6	
1941	39.0	40.2	39.1	
1942	49.0	40.3	41.1	
1943	19.7	40.5	24.2	20.2
1944	29.2	40.6	31.2	31.3[a]
1945	40.7	40.7	38.8	41.9
1946	59.2	40.9	42.2	53.3
1947	37.6	41.0	37.2	42.4
1948	42.0	41.1	44.2	39.1
1949	45.0	41.3	35.6	34.5
1950	43.5	41.4	41.4	39.7
1951	41.9	42.7	43.5	40.3
1952	37.0	44.1	39.7	37.6
1953	48.4	45.5	44.9	43.8
1954	52.1	46.9	48.8	53.8
1955	52.8	48.3	49.6	51.6
1956	33.2	49.7	46.4	35.1
1957	46.7	51.1	51.0	47.6
1958	54.8	52.6	60.4	55.8
1959	44.2	54.0	51.1	43.4
1960	61.5	55.4	60.9	59.7
1961	50.3	56.8	53.9	42.8
1962	57.7	58.2	63.8	62.8
1963	58.5	59.6	63.7	53.7
1964	68.7	61.1	63.2	68.7
1965	74.4	62.5	69.1	67.7
1966	64.2	63.9	65.6	69.2
1967	58.2	65.3	67.5	65.0
1968	68.5	66.7	65.2	64.2
1969	68.5	68.1	70.6	63.2
1970	69.0	67.1	68.4	71.7
1971	63.0	66.7	71.3	66.2
1972	72.0	66.3	70.9	71.8
1973	60.0	65.9	65.9	56.2
1974	61.1	65.4	67.7	64.1
1975	68.4	65.0	62.6	70.7
1976	61.4	64.6	69.3	62.1
1977	68.7	64.2	67.4	78.8
1978	67.5	63.8	66.6	68.8
1979		63.4		61.9

*Monthly climate data # Weekly climate data a).90 gamma

Table A-5. Gratiot County Corn Yields, Actual and Predicted

Year	Actual Yield	Yield Trend	Pred.* Yield	Pred.# Yield
1892	31.0	34.7	33.5	
1893	30.0	34.7	30.5	
1894	28.0	34.6	31.3	
1895	36.0	34.6	32.8	
1896	36.0	34.6	30.5	
1897	38.0	34.6	36.5	
1898	37.0	34.6	34.1	
1899	37.0	34.6	35.0	
1900	39.0	34.6	38.3	
1901	42.0	34.6	35.3	
1902	39.0	34.6	35.5	
1903	33.0	34.6	39.9	
1904	32.0	34.6	33.1	
1905	36.0	34.6	37.8	
1906	40.0	34.6	38.4	
1907	36.0	34.6	31.6	
1908	39.0	34.5	37.5	
1909	37.0	34.5	30.9	
1910	32.0	34.5	30.7	
1911	36.0	34.5	30.6	
1912	30.0	34.5	39.3	
1913	39.0	34.5	34.4	
1914	33.0	34.5	38.5	
1915	28.0	34.5	34.4	
1916	23.0	34.5	29.6	
1917	24.0	34.5	30.2	
1918	22.0	34.5	27.0	
1919	48.0	34.5	33.9	
1920	44.0	34.5	33.7	
1921	40.0	34.5	39.8	
1922	40.0	34.4	34.4	
1923	35.0	34.4	35.4	
1924	26.0	34.4	33.2	
1925	39.0	34.4	36.1	
1926	34.0	34.4	29.9	
1927	33.0	34.4	33.8	
1928	34.0	34.4	34.1	
1929	29.0	34.4	31.3	
1930	25.0	34.4	31.2	
1931	34.0	34.4	35.5	
1932	32.0	34.4	35.8	
1933	31.0	34.4	33.3	
1934	18.0	34.4	32.4	
1935	41.0	34.3	33.3	
1936	33.0	34.3	33.3	
1937	37.0	34.3	33.3	
1938	33.0	34.3	35.5	
1939	38.0	34.3	35.7	
1940	30.0	34.3	33.3	
1941	40.0	34.3	34.9	
1942	46.0	34.3	31.3	
1943	34.8	34.3	31.1	29.6
1944	39.2	34.3	33.5	34.2
1945	37.3	35.1	34.1	29.4
1946	32.1	37.2	35.4	33.5
1947	31.9	39.2	40.2	35.0
1948	42.6	41.2	40.3	34.5
1949	56.0	43.3	44.4	55.8
1950	43.5	45.3	47.7	41.9
1951	42.9	47.4	49.3	41.2
1952	56.5	49.4	52.2	60.6
1953	51.6	51.4	50.8	45.5
1954	49.7	53.5	50.8	58.4
1955	48.1	55.5	57.7	46.3
1956	51.1	57.5	56.8	51.0
1957	48.5	59.6	58.7	53.7
1958	54.7	61.6	61.3	56.0
1959	63.2	63.6	67.7	71.3
1960	66.1	65.7	66.9	71.1
1961	76.2	67.7	71.0	74.3
1962	69.0	69.7	67.0	68.9
1963	80.4	71.8	71.1	72.5
1964	78.3	75.7	79.6	80.1
1965	62.8	76.2	74.2	66.7
1966	74.2	76.8	75.4	71.3
1967	73.0	77.3	75.3	82.3
1968	78.6	77.9	75.6	77.0
1969	86.4	78.5	76.9	85.4
1970	86.1	79.0	79.6	79.7
1971	65.1	79.6	79.1	70.1
1972	99.9	80.1	83.2	84.8
1973	95.0	80.7	81.3	88.0
1974	81.0	81.2	80.4	83.4
1975	99.0	81.8	93.1	95.7
1976	68.8	82.3	80.4	77.5
1977	62.1	82.9	84.7	79.1
1978	87.6	83.4	80.9	91.0
1979		84.0		72.1

*Monthly climate data #Weekly climate data

Table A-6. Gratiot County Dry Bean Yields, Actual and Predicted

Year	Actual Yield	Yield Trend	Pred.* Yield	Pred.# Yield
1895	8.2	8.3	7.5	
1896	9.1	8.3	8.3	
1897	8.6	8.3	7.8	
1898	6.7	8.3	8.0	
1899	9.0	8.3	6.9	
1900	10.8	8.3	9.7	
1901	10.8	8.3	8.5	
1902	8.4	8.3	7.9	
1903	10.2	8.3	9.4	
1904	7.8	8.2	8.7	
1905	11.4	8.2	9.7	
1906	9.6	8.2	9.1	
1907	8.4	8.2	7.4	
1908	10.8	8.2	8.8	
1909	9.0	8.2	7.5	
1910	9.0	8.2	7.2	
1911	7.2	8.2	7.2	
1912	7.2	8.2	8.8	
1913	8.4	8.1	9.2	
1914	6.6	8.1	9.0	
1915	5.4	8.1	8.8	
1916	3.6	8.1	5.3	
1917	6.1	8.1	7.7	
1918	5.4	8.1	7.1	
1919	7.9	8.1	7.7	
1920	10.0	8.1	9.1	
1921	6.0	8.1	7.9	
1922	7.8	8.0	7.9	
1923	8.4	8.0	8.9	
1924	7.8	8.0	9.5	
1925	8.4	8.0	9.1	
1926	7.8	8.0	6.8	
1927	6.0	8.0	6.9	
1928	7.8	8.0	9.2	
1929	5.6	8.0	6.1	
1930	3.0	8.0	5.1	
1931	4.8	7.9	6.2	
1932	9.0	7.9	8.9	
1933	7.2	7.9	5.8	
1934	4.2	7.9	6.6	
1935	9.6	7.9	7.8	
1936	6.0	7.9	7.2	
1937	8.4	7.9	8.2	
1938	9.6	7.9	8.3	
1939	10.8	7.9	7.7	
1940	7.8	7.8	6.8	
1941	8.4	7.8	7.9	
1942	10.8	7.8	7.5	
1943	9.6	7.8	7.3	10,1
1944	7.8	7.8	7,4	7.1
1945	10.1	7.8	8.1	9.1
1946	8.3	8.3	7.0	8.0
1947	7.7	8.8	9.5	6.5
1948	10.2	9.3	8.2	11.7
1949	12.6	9.8	10.4	11.1
1950	10.7	10.3	10.0	12.6
1951	12.3	10.8	11.1	12.1
1952	13.4	11.3	11.5	12.9
1953	12.1	11.8	11.8	11.1
1954	9.8	12.3	10.5	10.6
1955	9.7	12.8	13.2	11.3
1956	14.6	13.3	14.4	15.2
1957	8.0	13.7	13.3	9.0
1958	12.0	14.2	14.8	12.8
1959	12.0	14.7	15.6	13.0
1960	17.0	15.2	15.7	15.7
1961	17.5	15.7	16.6	18.1
1962	17.0	16.2	16.0	15.6
1963	20.3	15.2	15.5	18.6
1964	13.8	14.7	15.3	14.0
1965	9.9	14.3	13.9	14.8
1966	12.9	13.9	14.1	13.1
1967	11.2	13.4	13.0	11.5
1968	11.1	13.0	11.3	11.0
1969	13.5	12.6	11.5	10.8
1970	11.0	12.2	12.6	11.1
1971	9.3	11.7	11.1	10.7
1972	12.7	11.3	12.0	12.1
1973	11.5	10.8	11.2	10.2
1974	11.0	10.4	11.1	9.8
1975	9.4	10.0	10.2	9.3
1976	10.3	9.5	8.6	10.9
1977	11.0	9.1	10.1	9.7
1978	11.8	8.7	8.6	10.7
1979		8.2		10.3

Units: cwt/acre *Monthly climate data #Weekly climate data

Table A-7. Gratiot County Oat Yields, Actual and Predicted

Year	Actual Yield	Yield Trend	Pred.* Yield	Year	Actual Yield	Yield Trend	Pred.* Yield	Pred.# Yield
1892	28.1	31.2	36.9	1936	14.0	39.5	31.4	
1893	28.0	31.4	24.9	1937	37.0	39.7	35.6	
1894	38.9	31.5	31.9	1938	40.0	39.9	41.8	
1895	30.9	31.7	35.1	1939	35.0	40.1	38.1	
1896	36.5	31.9	35.8	1940	55.0	40.3	37.3	
1897	36.2	32.1	30.1	1941	43.0	40.5	44.7	
1898	37.3	32.3	30.9	1942	52.0	40.7	49.5	
1899	39.0	32.5	36.3	1943	27.4	40.9	36.5	33.0
1900	41.0	32.7	35.9	1944	36.6	41.1	35.6	34.3
1901	31.0	32.9	27.5	1945	50.3	41.3	50.5	51.4
1902	42.0	33.1	40.5	1946	53.2	41.4	45.4	47.7
1903	32.0	33.3	37.2	1947	46.8	41.6	42.5	47.9
1904	17.0	33.5	30.0	1948	46.0	41.8	45.5	42.7
1905	36.0	33.6	38.5	1949	39.0	42.0	38.4	35.3
1906	33.0	33.8	39.4	1950	46.6	42.2	37.2	42.9
1907	22.0	34.0	10.1	1951	44.6	42.4	41.0	43.3
1908	33.0	34.2	32.4	1952	37.0	42.6	38.6	40.0
1909	32.0	34.4	28.2	1953	38.9	42.8	35.5	39.3
1910	40.0	34.6	37.2	1954	45.8	43.0	46.0	41.5
1911	31.0	34.8	31.2	1955	46.7	43.2	43.9	43.2
1912	35.0	35.0	38.4	1956	33.0	43.4	41.8	42.7
1913	37.0	35.2	37.4	1957	43.6	43.5	44.4	41.5
1914	31.0	35.4	40.8	1958	61.1	43.7	50.0	51.2
1915	44.0	35.5	46.8	1959	41.7	55.5	52.4	55.0
1916	33.0	35.7	36.4	1960	61.5	55.9	60.9	58.1
1917	44.1	35.9	36.2	1961	52.2	56.3	54.7	61.8
1918	44.0	36.1	38.6	1962	58.6	56.7	59.7	57.4
1919	37.2	36.3	34.3	1963	60.0	57.1	54.8	54.3
1920	39.0	36.5	40.2	1964	61.1	57.5	54.8	59.9
1921	19.0	36.7	30.3	1965	59.7	57.9	57.2	63.1
1922	42.0	36.9	38.1	1966	54.3	58.3	51.3	57.2
1923	32.0	37.1	33.0	1967	63.1	58.7	58.2	58.1
1924	38.0	37.3	40.7	1968	61.9	59.1	64.9	60.7
1925	36.0	37.4	38.0	1969	65.8	59.5	62.5	66.5
1926	40.0	37.6	36.5	1970	68.0	59.9	58.5	61.4
1927	32.0	37.8	38.0	1971	52.9	60.3	58.6	55.2
1928	49.0	38.0	42.3	1972	61.1	60.7	60.6	65.5
1929	23.0	38.2	36.5	1973	60.0	61.1	60.0	58.2
1930	49.0	38.4	36.8	1974	58.0	61.5	65.1	64.7
1931	39.0	38.5	35.6	1975	65.2	61.8	56.4	59.9
1932	32.0	38.8	35.3	1976	56.0	62.2	59.4	59.8
1933	34.0	39.0	32.2	1977	61.0	62.6	67.3	64.3
1934	27.0	39.2	31.4	1978	59.0		[illegible]	68.4
1935	35.0	39.4	38.6	1979				68.0

*Monthly climate data #Weekly climate data

Table A-8. Gladwin County Corn Yields, Actual and Predicted

Year	Actual Yield	Yield Trend	Pred.* Yield	Year	Actual Yield	Yield Trend	Pred.* Yield
1926	27.0	26.6	24.9	1952	42.8	37.1	43.2
1927	33.0	26.6	25.4	1953	40.8	38.5	40.4
1928	33.0	26.7	30.3	1954	35.4	40.0	36.7
1929	12.0	26.7	14.0	1955	44.2	41.4	47.2
1930	15.0	26.8	23.1	1956	44.1	42.8	42.5
1931	32.0	26.8	25.7	1957	47.1	44.2	49.0
1932	31.0	26.8	29.9	1958	38.8	45.7	42.5
1933	29.0	26.9	25.9	1959	53.2	47.1	49.7
1934	28.0	26.9	22.6	1960	38.8	48.5	47.2
1935	28.0	26.9	29.4	1961	48.7	49.9	50.0
1936	21.0	27.0	24.4	1962	54.6	51.4	49.3
1937	38.0	27.0	30.2	1963	57.1	52.8	55.2
1938	27.0	27.1	25.2	1964	56.2	54.2	55.5
1939	24.0	27.1	27.9	1965	46.5	55.6	50.2
1940	20.0	27.1	30.0	1966	64.6	57.0	57.4
1941	26.3	27.2	24.4	1967	61.1	58.5	56.9
1942	33.0	27.2	28.5	1968	63.2	59.9	60.2
1943	28.9	27.2	29.7	1969	65.2	61.3	67.5
1944	31.8	27.3	24.4	1970	67.4	62.7	72.2
1945	29.3	27.3	23.8	1971	47.9	64.2	58.4
1946	19.4	27.4	28.9	1972	81.9	65.6	77.8
1947	23.2	27.4	23.1	1973	66.0	67.0	68.0
1948	31.4	31.4	27.0	1974	70.0	68.4	71.3
1949	41.0	32.8	36.6	1975	76.0	69.9	77.9
1950	37.5	34.3	34.4	1976	65.0	71.3	73.3
1951	29.9	35.7	36.2	1977	59.2	72.7	60.2
				1978	77.8	74.0	66.8
				1979		75.3	

*Monthly climate data
Units: bushels/acre

Table A-9. Gladwin County Oat Yields, Actual and Predicted

Year	Actual Yield	Yield Trend	Pred.* Yield
1926	29.0	21.4	24.9
1927	16.0	21.9	19.6
1928	27.0	22.4	27.9
1929	25.0	22.8	23.5
1930	32.0	23.3	21.1
1931	21.0	23.8	20.0
1932	27.0	24.3	21.8
1933	17.0	24.8	19.7
1934	20.0	25.3	18.3
1935	26.0	25.7	27.0
1936	14.0	26.2	23.6
1937	24.0	26.7	25.4
1938	27.0	27.2	27.8
1939	35.0	27.7	30.7
1940	38.7	28.1	26.9
1941	28.0	28.6	30.0
1942	40.0	29.1	32.5
1943	18.7	29.6	26.1
1944	31.3	30.1	29.5
1945	36.4	30.6	36.0
1946	13.6	31.0	30.8
1947	28.5	31.5	20.3
1948	40.0	32.0	36.9
1949	29.0	32.5	30.9
1950	32.4	33.0	28.5
1951	39.8	33.4	36.6
1952	27.8	33.9	32.8
1953	27.3	34.4	32.8
1954	33.4	34.9	31.9
1955	38.6	35.4	41.7
1956	29.0	35.9	31.1
1957	37.3	36.3	38.0
1958	42.8	36.8	41.2
1959	41.7	37.3	40.1
1960	40.8	38.3	45.9
1961	38.6	38.5	35.3
1962	35.5	38.7	38.9
1963	46.7	39.2	40.4
1964	36.2	39.7	38.4
1965	44.8	40.2	42.2
1966	26.7	40.7	31.7
1967	36.9	41.2	36.3
1968	51.1	41.6	45.3
1969	51.0	42.1	51.4
1970	48.8	42.6	42.5
1971	32.0	43.1	36.2
1972	44.0	43.6	51.6
1973	33.8	44.0	41.6
1974	40.4	44.5	46.7
1975	52.0	45.0	48.3
1976	46.8	45.5	44.4
1977	51.0	46.0	49.3
1978	53.1	46.5	48.2
1979		47.0	

*Monthly climate data
Units: bushels/acre