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To the Graduate Council:

I am submitting herewith a dissertation written by Garey Banks Perkins entitled "Estimation of Corn Yield Response to Selected Weather Variables in West Tennessee." I recommend that it be accepted in partial fulfillment of the requirements for the degree of Doctor of Philosophy, with a major in Agricultural Economics.

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ESTIMATION OF CORN YIELD RESPONSE TO SELECTED WEATHER VARIABLES IN WEST TENNESSEE

A Dissertation

Presented to

the Graduate Council of

The University of Tennessee

In Partial Fulfillment

of the Requirements for the Degree

Doctor of Philosophy

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by

Garey Banks Perkins

August 1971

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ABSTRACT

This study analyzed the effects of varying soil moisture conditions on per acre corn yields for selected counties in West Tennessee. The basic assumption underlying the study was that abnormal moisture conditions during the growing season adversely affected corn yield. It was hypothesized that too much as well as too little available soil moisture contributed to reductions in per acre corn yields.

To test the hypothesis, a 14 county area of West Tennessee was selected as a study area. These counties were selected because they produced a substantial portion of the total corn crop grown in Tennessee.

The objectives of the study were as follows:

1. To make quantative estimates of corn yield response to soil moisture and precipitation variables during the critical period of the corn growing season in selected counties in West Tennessee.

2. To evaluate the incremental changes in moisture variables during the critical months of the corn growing season.

3. To construct precipitation probability distributions for counties included in the study, and to use the distributions to predict changes in monthly moisture conditions.

To achieve the objectives, two types of analyses were used. One involved the use of Palmer's Drought Index and the other included the use of two-week precipitation totals.

The regression equation containing the Index explained about 85 percent of the corn yield variation. The results indicated that for

drier than normal conditions during the months of May, July, and August, increases in the Index generally brought about increased corn yield. Increases in the Index to slightly wetter than normal were associated with increased yield. Further increases in the Index, to extremely wet conditions, were associated with decreased yield. Results for June were irrational with respect to the signs and magnitudes of the coefficients.

The regression equation containing inches of precipitation by two-week period explained about 38 percent of the corn yield variation. Results of this analysis closely paralleled those of the equation containing Index values. However, coefficients for the first two-week periods in May, June, and August exhibited irrational signs.

As precipitation rose from 0.00 to 4.00 inches, corn yield first increased at a decreasing rate then declined. Marginal physical product became negative at 4.00 inches of precipitation in the second period of both May and June, and at 1.00 inch in the second period of July. In the first period in July and the second period in August, marginal physical product did not diminish even with 4.00 inches of precipitation.

A combination of data from Palmer's Drought Index and precipitation probability distributions provided a model which was used in predicting changes in soil moisture conditions. The model accurately predicted monthly changes during the May through August period about 61 percent of the time. This model was seen as a valuable tool for both policy makers and for individual producers.

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CHAPTER I

INTRODUCTION

> The atmospheric environment rules agriculture. In the long terms of climate it governs what crops can be profitably grown in a given region. In shorter time intervals, as weather, it determines the yields, and hence the successes and failures in individual years. The ecology of (crops and) livestock is profoundly influenced by meterological entities. The incidence and spreading of many pests depends on the whims of the weather. (13, p. 1)

Justification for the Study

Researchers generally agree that weather affects crop yields. There is less agreement concerning the magnitude, direction, and importance of such effects. Thus, there is a need to identify and to quantify the effects of weather variables on crop production. A knowledge of these relationships may aid producers in the formulation and selection of alternative production strategies. At present there is no adequate method of handling the effects of weather in agricultural production functions.

The problem is how to develop an adequate procedure for determining the effects of changes in weather variables on crop yields. These changes in turn affect the economic situation of individual producers, counties, states, and the entire agricultural sector of the economy.

Researchers in production economics admit that weather is an important variable. But of the method of handling it is said

(7, p. 7): "The usual treatment in analyses that involve a weather input is to assume that weather conditions will be average."

Examination of climatological data for any agricultural area confirms that weather variables are not without extreme variation. Such variations are observed on an annual as well as a seasonal basis. Even for years with little variation in precipitation totals, for example, the seasonal distribution of precipitation may result in wide fluctuations in crop yields.

Numerous studies have been made dealing with the effects of changes in weather variables on crop yields. The definition and treatment of weather variables in many studies raises some important theoretical and statistical questions. The practice in many production function approach studies has been to either assume weather as average or to relegate its influence to the error term in the statistical formulation of the production function. An attempt was made in this study to treat soil moisture conditions as explicit independent variables in a regression analysis.

One approach to weather crop yield response research has been to simply examine the effects of variations in precipitation on crop yields. The weaknesses of this procedure are obvious. Available moisture in the soil and not precipitation quantities alone affect crop yields. Taking an extreme case as an example, normal monthly quantities of precipitation might occur during the first two days of June and the last two days of July. Thus, precipitation totals for each of the months would be normal and adequate for average corn production. Distribution of the

precipitation, however, would result in corn yield being drastically reduced. A consideration of shorter time periods would not greatly diminish the probability of occurrence of this phenomenon.

In spite of this problem, studies regressing corn yield on precipitation totals have resulted in relatively good fits of the regression equations to the data. One reason for this is that precipitation does serve as a surrogate variable for available soil moisture. Another reason is that data were generally aggregated over relatively large geographical areas. Generally, aggregation of data in weather crop yield studies increases the goodness of fit of the regression equations, evaluated in terms of the coefficient of determination. In many instances, regressing state average corn yields on state annual precipitation totals results in relatively good statistical fits.

Weather variables affect corn yields both directly and indirectly. For example, a positive relation has been observed (9, page 70) between available soil moisture and nitrogen application effectiveness.

> Weather differences may be expected to cause extreme variations in the fertilizer-yield relationships obtained over a period of years, making the optimal rate of fertilization estimated for one set of weather conditions inappropriate for a different set.

Purpose of the Study

This study proceeded under the hypothesis that weather induced variations in corn yields were both identifiable and measurable. The primary concern was not that weather influenced corn production, but was the magnitude of such influences. This study was directed to the objective of computing the quantative values of these influences.

Values thus obtained were then subjected to further analysis in an attempt to determine the effects of incremental changes in the weather variables.

Objectives

The objectives of the study were as follows:

1. To make quantative estimates of county average corn yield response to available soil moisture and precipitation during the critical period of the corn growing season in selected West Tennessee counties.

2. To estimate the effects of incremental changes in weather variables for the same area and time period.

3. To compute precipitation probability distributions for counties included in the study, and to use them in predicting changes in monthly moisture conditions.

Data Sources

County average corn yields were obtained from the Tennessee Federal-State Crop Reporting Service statistical reports. County data were available only for the period from 1949 through 1969.

Available climatological data were utilized to compute the soil moisture availability Index. This Index was then used as an independent variable in the regression equations.

Daily readings on precipitation and maximum and minimum temperatures and other data used in computing the drouth Index were taken from records of The United States Weather Bureau. Tapes containing these

data were obtained from the National Climatic Center in Asheville, North Carolina.

Area of the Study

Data were obtained for fourteen counties in Tennessee. As shown in Figure 1, these counties were all located west of the Tennessee River. These counties were selected for this study because approximately 40 percent of the corn grown in Tennessee during the time period of this study was grown in these fourteen counties. Appendix Table 9 shows total acreage of corn, and the average yield for each of the counties for the years 1949-1969, inclusive. Counties and weather reporting stations selected, Table 1, were assumed to be representative of the West Tennessee area.

Data Limitations

A drouth Index based on historical climatological data from a representative weather reporting station was computed for each of the counties in the study area. With the exception of Shelby and Madison Counties, there was only one weather reporting station in each county. It was recognized that some intracounty variation existed which was not accurately reflected in data from a single station. However, this level of aggregation was not thought to greatly distort the estimate of actual climatological phenomena existing within counties.

One disadvantage of using data from such small geographic areas was that disaggregation of weather and yield data tends to lessen the goodness of fit of the regression equation to the data. Accuracy



Figure 1. Area of the Study.

TABLE 1

COUNTIES AND WEATHER STATIONS SELECTED,
WEST TENNESSEE

County	Station
Obion	Union City
Dyer	Newbern
Tipton	Covington
Shelby	Memphis Airport
Fayette	Moscow
Hardeman	Bolivar
McNairy	Selmer
Madison	Jackson Experiment Station
Haywood	Brownsville
Gibson	Milan
Carroll	Huntington
Weakley	Martin College
Henry	Paris
Hardin	Savannah

increases with aggregation because of the "leveling out" effects of aggregation. The influence of both above and below normal conditions tends to be lessened or to balance out when aggregates are used.

County average yield data are less than ideal for the purposes of this analysis because yield responses to weather at higher levels of production cannot be observed. Thus, the effects of weather observed on county average corn yields will seriously underestimate weather effects on yields under higher levels of management and technology.

CHAPTER II

METEROLOGICAL CONSIDERATIONS

Meterological Drouth

The problem of drouth is apparently as old as mankind. According to the Holy Bible, Genesis, Chapter 41, a severe seven year drouth occurred in the ancient land of Egypt. Joseph gained fame and fortune by being able to predict the drouth and to prepare the nation for it. Such accuracy of prediction has yet to be achieved in the ensuing centuries.

The term drouth has been used in such a variety of ways that, like many words in common usage, it has become almost meaningless. For example, drouth means one thing to an agronomist and another to a newspaper editor.

Even among agronomists there is no unaminity of thought as to the proper definition of drouth. To some agronomists, the level of available soil moisture must diminish to zero before there is a definitional drouth. To others, the level of soil moisture must fall below some predetermined level. And to still others, drouth conditions are assumed to exist if available soil moisture is reduced to a level which results in suboptimal plant growth.

The farmer, perhaps better than anyone else, understands what drouth means. To him, it means that a shortage of available soil moisture has affected his crop, and subsequently, his economic situation.

Lack of agreement is not limited to the definition of drouth. There is disagreement also as to how the word should be spelled and pronounced. Two spellings and pronunciations are common. Drought (pronounced like "trout" or "snout") and drouth (like "south" or "mouth") are commonly observed variations. The latter has been used throughout this study, with the exception of direct quotations from sources which used the former spelling, and when a specific index was mentioned.

If drouth is to be meaningful, it is necessary to give it a more precise definition. A consistent definition is required before any useful drouth index can be computed. Drouth occurrence and intensity are intricately correlated with both the magnitude and the distribution of precipitation during some given period of time, i.e., the growing season for a crop. This, however, is not all that must be considered. Diminution or magnification of the influence of drouth may vary with soil type and the crop that is grown. Also, an almost unlimited array of other factors may influence drouth intensity. Ewalt, Doll, and Decker (6, p. 7) pointed out that: "A meaningful definition of agricultural drouth must take into account all of the agronomic and climatic conditions which have a significant effect upon the moisture available for use by the crop."

A very complex set of relations exists for determining drouth existence and severity. No attempt was made in this study to examine or even to isolate all the factors which were thought to affect drouth severity.

Soil Moisture Base

The soil can be visualized as a sponge capable of holding water. Not all of the water held in the soil is available for use by the crop. Three major factors determine the ability of the soil to hold water for crop use. The first is the amount of moisture held in the range between field capacity and the wilting point of the plant.

> Field capacity is defined as the amount of water, expressed as a percentage of the dry weight which the soil will retain after being thoroughly soaked and allowed to drain for one to three days. (6, p. 9)

The permanent wilting point is reached when the water in the soil is held at a tension at which plants are unable to extract quantities essential for maintenance of their normal physiological functions. The water holding capacity generally is expressed as the fraction of an inch of water held per inch of soil depth. This capacity varies with soil type.

A second factor which affects the moisture holding capacity of the soil is the effective rooting depth of the crop. The ability of the plant to draw moisture from the soil depends on the volume of soil from which moisture may be drawn. Thus, the moisture holding capacity of the soil in conjunction with the dimensions of the rooting zone determines the available soil moisture which is considered available to the plant. Soil type and physiological characteristics of various plants form the parameters for the effective rooting depth of crops.

A third factor which affects soil moisture availability is the plant's physiological reaction to soil moisture stress. The quantity of water held by the soil in the range between field capacity and the

wilting point is defined as the water holding capacity of the soil.

Once the available soil moisture base for a given soil and crop combination is determined, additional information required to compute daily soil moisture balances can be obtained from climatological records. Daily precipitation and daily minimum and maximum temperatures, which are required for computational purposes, are available for most weather stations. Temperature readings are used to obtain estimates of daily evapotranspiration rates. Evapotranspiration is difficult to measure directly but can be estimated through the use of recorded climatic variables. Researchers have developed several formulae which can be used to obtain estimates of evapotranspiration (14, 22, 24, 26). In this study, a method devised by Wayne C. Palmer (15) was used.

Drouth Measurement

Van Bavel (26) did much of the early work in developing a procedure for computing what is known as the drouth day. His procedure involved an accounting method of computing available soil moisture on a daily basis. This method consisted of selecting a level of soil moisture for a specific crop and soil combination below which plant growth was adversely affected. A drouth day was considered to occur when available soil moisture fell below the critical level. Estimates were made by moisture balance computations of daily precipitation and evapotranspiration. A quantative measure of drouth was obtained by summing the number of days in which soil moisture fell below the critical level.

Drouth Day Concept

A drouth day was defined as follows by Van Bavel (26, p. 2).

> A drouth day is a 24-hour period in which the soil moisture stress exceeds a limit, which, on the basis of experimental evidence, may be taken as a point at which the productive processes of the crop are being appreciably decreased.

In using drouth days as a measure of moisture availability, the implicit assumption was that moisture deficiency was the predominant cause of yield variability. While truthful, this assumption was incomplete. The use of such a measure neglects yield variation resulting from excessive moisture. Time distributions of precipitation quantities exhibits not only periods of below normal but also periods considerably above normal.

Palmer's Drought Index

For maximum usefulness, any measure of weather used in explaining yield variation should be computed independently of yield data. It should also be derived independently of any assumptions relating to technological change over the time period under consideration. The Index used in this study was computed so as to be independent of both yield data and technology. It is an approximation of the deviation from normal moisture availability, where one single Index number incorporates many meterological phenomena each of which is relevant to moisture availability.

In discussing his procedure, Palmer (15, p. 4) says:

> Stated in the simplest terms the problem here is to develop a method for computing the amount of precipitation that should have occurred in a given area during a given period of time

> in order for the "weather" during the period to have been normal--normal in the sense that the moisture supply during the period satisfied the average or climatically expected percentage of the absolute moisture requirements.

Palmer (15, p. 4) goes on to say that his procedure determines:

> How much precipitation should have occurred during a given period to have kept the water resources of the area commensurate with their established use.

It is then quite easy to compare the amount of precipitation that actually occurred with the amount that should normally occur. This comparison provided an index of the shortage or excess of moisture.

In providing a quantative measure of drouth from meterological data, Palmer followed Thronthwaite's method in developing a system of hydrologic accounting. Measured precipitation, P, constitutes the system inflow. Evapotranspiration, ET, and runoff, RO, constitute the system outflow. The quantity of moisture in the system may be measured as inches of water available to the plant. This quantity is limited by the available water capacity, AWC, of the soil. The available water capacity is, in turn, affected by the soil type and geographical location of the land. The available water capacity of the soil in the West Tennessee area used in this study was the same as that used by Palmer in his computations for the same area, 4.00 inches, 1.00 in the surfact layer and 3.00 in the underlying layer. The upper layer of the soil was defined by Perrin (19, p. 58) as: "that depth of soil necessary to hold one inch of moisture at field capacity".

Precipitation was measured as the average monthly precipitation at the weather station selected for each county. For purposes of this study, only one weather station for each of the counties was used.

The available water capacity of the soil in a county was assumed to be constant over time.

Runoff from the system was assumed to occur when precipitation exceeded evapotranspiration plus the potential recharge capacity of the soil. Although this was an approximation to runoff measurement, Palmer pointed out that his estimates differed little from those made by the Geological Survey (15). His method provided a means of approximating moisture demand or outflow. The method used was based on temperature measurements adjusted for season and latitude. Moisture demand, computed by Palmer, was expressed as inches of moisture which were evaporated and transpired under ideal moisture and vegetative conditions. Potential evapotranspiration, PET, provided an upper limit for actual evaporation expected during the period. Monthly periods were used in this analysis.

Potential evapotranspiration normally exceeded actual evapotranspiration because the soil was normally at less than field capacity of available moisture.

Palmer (15, p. 27) described the procedure used for estimating actual evapotranspiration as follows:

> In the moisture accounting it is assumed that evapotranspiration takes place at the potential rate from this surface layer until all the available moisture in the layer has been removed. Only then can moisture be removed from the underlying layer of soil. Likewise, it is assumed that there is no recharge to the underlying portion of the root zone until the surface layer has been brought to field capacity. And . . . the loss from the underlying layer depends on initial moisture content as well as on the capacity (AWC) of the soil system.

This hydrologic accounting procedure permits only approximations of the various measures of evapotranspiration and of available soil

moisture. The accuracy of these approximations is, of course, subject to question. A critical test of the usefulness of the index is its ability, ceteris paribus, to explain crop yield variation.

Palmer's procedure provided a method of estimating the magnitude of evapotranspiration which would represent "normal" evapotranspiration, given the actual moisture demand for that period of time. This derived evapotranspiration was termed "climatically appropriate for existing conditions" and is labeled, $\hat{ET}$. $\hat{ET}$ may be defined as the level of evapotranspiration required to yield the average ratio of ET to PET. The departure of observed ET from $\hat{ET}$ provided an index of departure from normal moisture availability. The index was used to examine the influence of weather applied to the corn production process. Within limits, a priori expections would be that a positive value of the index would be associated with higher than normal yields, while a negative value would be associated with lower than normal yields. It would also be expected that beyond some limit, positive values of the index would also be associated with lower than average yields. Thus, optimal yields would be expected to occur at or near normal weather conditions.

Precipitation as an Independent Variable

Inches of precipitation during two-week periods of the May through August period were included as independent variables in a regression equation. This was done to permit a comparison of the explanatory ability of soil moisture conditions as defined in the two separate equations.

Biweekly precipitation totals were obtained by summing the daily precipitation quantities over two-week periods. Due to the irregular number of days in the months, a summation was made over the first 15 days of the month which was defined as the first two-week period. A summation was made over the remaining days in the months which was defined as the second two-week period. Precipitation totals thus computed were then used in a quadratic equation regression analysis.

CHAPTER III

ECONOMIC AND STATISTICAL CONSIDERATIONS

Previous Research

Considerable research has been done relating weather to crop yield response. Perrin (19) reported that between 1900 and 1930, there were 2,324 studies made of crop response to weather variables. The number of studies made in that period of time verify the fact that it has been long recognized that to estimate a crop production function, account must be taken of the influence of weather.

One of the earliest weather crop yield studies was made by H. L. Moore (13). In 1914, he published the results of a study of the effects of weather on crop yield. Moore attempted to show that weather cycles existed which affected crop yields and, in turn, provided the basis for economic cycles. No attempt was made by Moore to quantify the results of weather variables on crop yields.

Henry A. Wallace, in 1920, used monthly average precipitation and temperature as variables in an attempt to estimate corn yield in the Corn Belt (27). He concluded that corn was grown in the Corn Belt because it was more suited for corn production. For less suitable areas, he concluded that corn yields were more responsive to changes in weather variables.

One of the early attempts to compute a weather index was made by James L. Stallings (21). His approach was based primarily on experimental plot data.

In support of this approach, Stallings (21, p. 1157) said:

> If time series of yields for particular crops can be obtained from experimental plots in the areas where these crops are grown and where as many variables as possible have been held constant, the remaining variation in yields, after any trends have been removed, are due primarily to weather. Any other variation not accounted for is assumed to be randomly and normally distributed with an expected value of zero.

No distinction was made between direct and indirect weather influences. This, he said (21, p. 1157), was: "Because the effects of weather are measured in net, ex post, and presumably independent of economic and other factors."

What Stallings wanted was experimental plot data with all variables, except weather, held constant (21, p. 1157). One of the problems with his approach, however, was that experimental plot data were not available in the quantity and with the degree of accuracy desired. Time series data were used from experimental plots for which as many variables as possible had been held constant. On this basis, he assumed that variations in yields remaining after the effects of trend had been removed were due to weather.

Stallings measured the effects of weather as a ratio of actual yield to computed yield. His method is illustrated in Figure 2, where:

Y = actual per acre corn yield,

$\hat{Y}$ = computed per acre corn yield, and

T_i = time, in years, where $i = 1, \ldots n$

To illustrate the use of Stallings' Weather Index (SWI), consider year 1, (T_1). The index value for that year is computed as follows:

$$SWI = Y_1 / \hat{Y}_1$$

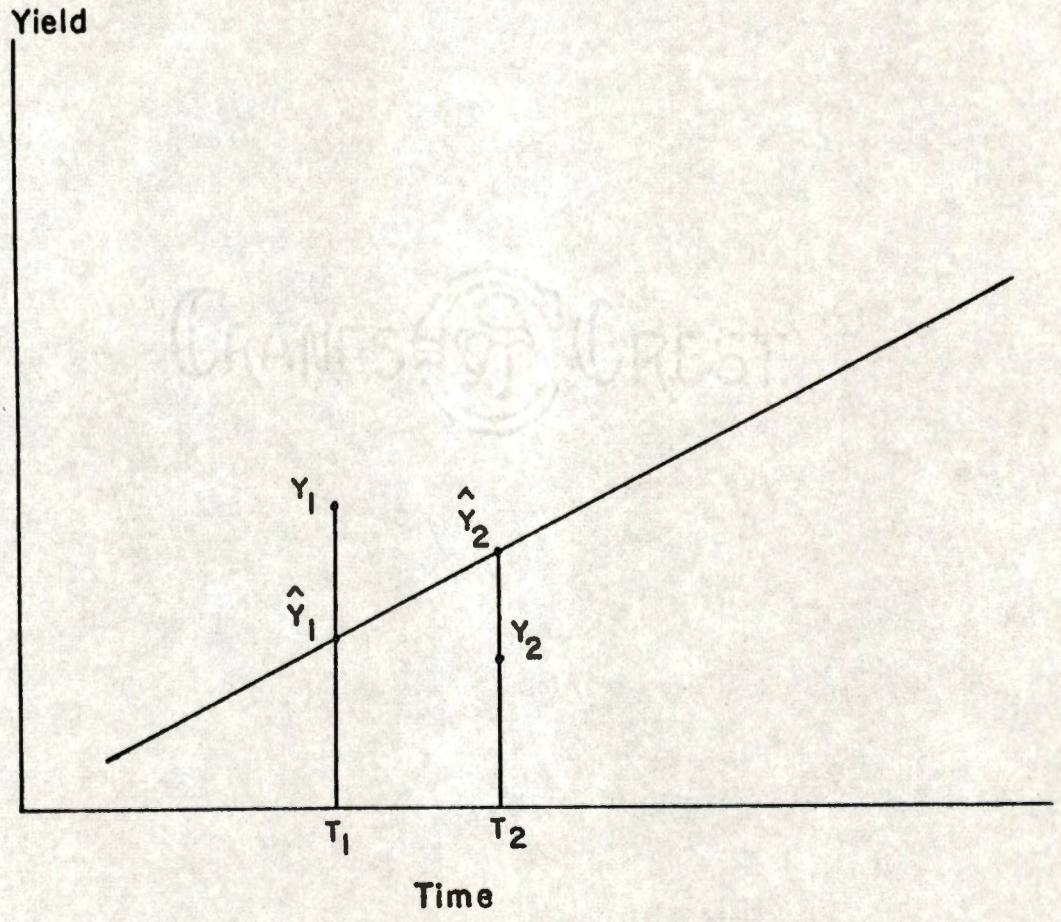


Figure 2. Stallings' Weather Index, A Graphical Summary.

The Index, in this case, for year 1 would be greater than unity because the actual yield exceeded the expected yield. In a second year, (T_2), the Index value is less than unity because the actual yield was less than the computed yield.

Stallings' procedure violated one of the criteria for a good weather index as set forth in Chapter II. It was not computed independently of corn yield data. Stallings did attempt, however, to measure the effects of weather independently of technology. He did this by assuming that over time, technology remained constant on the experimental plots.

Since his procedure was a ratio of one yield statistic to another, it had little or no predictive ability.

Ewalt, Doll, and Decker (6) selected phenological variables in an attempt to explain corn yield variation in Missouri. Three weather variables were used. They were: (1) drouth days computed by Penman's method, (2) drouth days computed by Thornthwaite's method, and (3) inches of precipitation.

Results reported in the study showed that the equation using precipitation as the independent variable yielded the highest coefficient of determination, R^2. Coefficients of determination reported for the equations containing the three independent variables were as follows:

Independent Variable	Coefficient of Determination, R^2
Drouth days (Penman's method)	0.68
Drouth days (Thornthwaite's method)	0.52
Inches of precipitation	0.75

The authors concluded (6, p. 20) that: "Weekly rainfall explained more variation in corn yields than either of the other two methods."

McQuigg and Doll (12) examined the decision making process of farm managers, taking into account weather variability. Weather, they pointed out, cannot be predicted without error; therefore, it is desirable for the farm manager to make production decisions based on as much knowledge as possible. This will allow managers to minimize risks associated with weather variability.

The authors (12, p. 7) pointed out that:

> Research in production economics is usually directed toward the maximization of profits, or the minimization of costs. The usual treatment in analysis that involves a weather input is to assume that weather conditions will be average.

Since weather conditions vary widely, producers need some basis for making management decisions under conditions of weather uncertainty. Better yet, they need some way to predict weather variability and to estimate its effects on their operation.

The authors treated weather variables as random variables. They developed a model to analyze a production situation involving random weather variables and applied the model to a grain drying process.

One of the latest studies relating weather and crop yield response was made by Louis M. Thompson (25). Thompson was concerned with determining "the optimum weather conditions affecting yield of soybeans" (25, p. 2). Technology was accounted for by the inclusion of a time trend variable in the regression equation.

Thompson (25, p. 2) concluded that: "Each weather variable tends to be related to yield in a curvilinear fashion."

Using both linear and quadratic equations to determine response curves, Thompson plotted the relationship of weather variables and soybean yield and found that the resulting curve resembled a parabola. The top of the parabola represented optimum conditions and maximum yields with yield dropping off in both directions from the optimum.

His conclusion was that a production function with available moisture as a factor of production approaches a normal production curve. Not unexpectedly, Thompson found that highest yields occurred in years with near normal temperature during the months considered.

Temperature and precipitation during June, July, and August were considered as separate independent variables. Conceptually, it appeared that some account should also be taken of the possible interaction of the two variables.

Thompson concluded that temperature, when considered independently of the other variables, was not a limiting factor in soybean production in Iowa. However, temperature has been shown to affect the evapotranspiration rate substantially (15). This rate, in turn, affects the soil moisture supply available to the plant.

The temperature-soybean response curves "topped out" at near-normal temperature levels. With precipitation, no such optimum or peak was observed. Thus, precipitation in July and August appeared to be the limiting factors in soybean production in Iowa. Additional inches of precipitation would have increased per acre soybean yield by about a one-to-one ratio. This indicated that each incremental inch of precipitation would have yielded one additional bushel of soybeans per acre.

Parrin (19, p. 60) pointed out some of the problems involved when several variables are used to represent technology.

> Even if we had accurate measures of all the variables that we believe are important, we would still be confronted with problems difficult of solution. A real source of difficulty . . . (is) . . . in actual practice many variables tend to change at the same time. And the changes in the variables are highly correlated. The increased use of tractors, fertilizer, and hybrid corn from the early 1930's . . . have tended to be parallel increases. Consequently, it is extremely difficult to isolate the effects of each of these important changes.

One problem encountered is the relatively high correlation between weather variables and technology. Weather influences the effectiveness of some technological advances. For example, a higher yielding hybrid corn variety might be more susceptible to insect and disease damage which might be more prevalent because of excessively dry or excessively wet weather. A more direct influence might be felt through the influence of varying levels of available soil moisture and "better" fertilizer or of heavier fertilizer applications. Thus, it was expected that both direct and indirect influences existed between weather and technological advances. Account may be taken of the direct influences of weather by examining the effects of weather on yields of experimental plots with varying technologies and with other factors held constant.

Desai (4) analyzed the effects of weather on wheat yield in Kansas under various types of cultural practices. Experimental plot data were used in his study. He concluded that weather influenced wheat yields differently under different cultural practices.

A number of studies have been made analyzing the effects of weather on crops with varying levels of fertilization (10, 11, 16, 17,

20). Holt (9) in a study of corn yield at the Jackson Tennessee Experiment Station found that there was a positive relation between fertilizer application and available moisture and their influences on corn yield.

It is sufficient, for the purposes of this study, to recognize that both direct and indirect influences existed. Trend was removed in an attempt to remove the effects of technology and to reduce the indirect influence of weather on corn yield. This analysis was concerned with the direct influences of weather on corn yield.

Production functions. Stigler (23, p. 106) defined a production function as: "The relationship between the rates of inputs of productive services and the rate of output of the product." Dell, Rhodes, and West (5, p. 59) said: "The production function is based on the idea that the amount of output of a production process depends upon the amount of input used in the process."

Thus, the output of corn in West Tennessee is assumed to depend upon the weather variable as well as upon the other factors of production.

The following generalized form of the production function may be used to describe the productive process for corn in West Tennessee.

(1) $$Y = f(X_1, X_2, X_3, X_k, \ldots, X_m)$$

where

Y = per acre corn yield,

X_1 = land,

X_2 = labor,

X_3 = capital, and

X_k to X_m = all other factors.

Often, the procedure is to examine one or more of the factors, holding the others constant. Such equations may be written as follows:

$$Y = f(X_1/X_2, \mu) \quad . \tag{2}$$

The effects of weather in equation (2) have been relegated to the error term, ε. An equation of the following type is often used to estimate the production function.

$$Y = A + B_1X_1 + B_2X_2 + B_3X_3 + \varepsilon \tag{3}$$

In this type of equation, the effects of weather are usually assumed to be included in the error term, as was the case in equation (2). To estimate the equation, the following formulation is used.

$$\hat{Y} = a + b_1x_1 + b_2x_2 + b_3x_3 \tag{4}$$

This equation may be estimated by using the least squares method with either the dependent variable or with the independent variables which include moisture conditions as explicit variables.

Multicollinearity. Multicollinearity existed among the various independent variables. This was inherent in the variables as they were defined and computed for this study. Since the existence and severity of drouth in July, for example, depended on conditions existing during

the previous month, multicollinearity was anticipated. There was also multicollinearity between the variables and their squared values and interaction terms, as they were used in the quadratic equations.

Economic Considerations

The economic basis for the present study is grounded in the theory of production economics. Since weather was considered to be an input for corn production, it was necessary to consider it in estimating a production function for corn.

Much research has dealt with corn production functions. However, in many of the studies, no attempt was made to include, explicitly at least, the effects of weather variables.

In the present study, an attempt was made to estimate a corn production function which included an explicit weather variable. The variable used was computed independently of both corn yield and technological changes.

CHAPTER IV

REGRESSION ANALYSIS

Trends in Per Acre Corn Yield

Linear trend equations were computed for each of the 14 counties included in the study. The results of these computations are shown in Table 2. Expected corn yields, thus computed, were subtracted from actual yields for each year to obtain yield deviations. The independent variable used to compute the trend was the last two digits of the year. The long-run trend was upward reflecting increasing technology over the study period. Annual increases in yield are seen as the coefficients of the trend variable in the equations in Table 2.

Trend was removed from the data in an attempt to remove the effects of technological change over the period of the analysis.

Average yields varied from a low of 32.48 bushels in Hardeman County to a high of 47.19 bushels in Obion County. Yields were generally higher in the northern tier of counties. The same counties experienced the most rapid increases in yields over the 21 year period. Dyer County led with an annual increase of 2.39 bushels per acre, while Shelby and McNairy Counties, both on the southern border of the state, had trends of 1.28 bushels per acre per year.

Regression Analysis

Determination of the effects of incremental changes in moisture conditions necessitated the use of nonlinear equations. Ceterus paribus,

TABLE 2

YIELD STATISTICS AND TREND EQUATIONS, SELECTED COUNTIES, WEST TENNESSEE, 1949-1969

County	Average yield	Standard deviation	Trend coefficient
Hardeman	32.48	11.21	1.38
Haywood	34.90	13.50	1.86
Tipton	33.79	10.80	1.36
Carroll	35.40	11.08	1.52
Madison	35.02	11.22	1.39
Weakley	39.33	13.42	1.94
Shelby	32.98	10.91	1.28
Gibson	39.13	12.92	1.79
Fayette	33.64	13.69	1.77
Dyer	44.74	16.15	2.39
Henry	39.30	11.89	1.70
Hardin	32.58	8.68	0.90
McNairy	33.19	9.83	1.28
Obion	47.19	14.77	2.16

corn yield was expected to first increase at an increasing then at a decreasing rate and finally to diminish as a result of adding extra units of a given productive input. A similar response was expected from incremental changes in the moisture condition variables. Testing of this hypothesis involved the fitting of nonlinear equations to the observed data. Various functional or mathematical forms were available.

In this chapter two analyses were made. One included as an independent variable Palmer's Drought Index computed on a monthly basis. The other included inches of precipitation by two-week period. Quadratic equations were used in both instances. It was hypothesized that the more complex measure of soil moisture conditions, Palmer's Drought Index, would provide a better explanation of corn yield variation. However, as was seen in the Ewalt, Doll, and Decker study (6), precipitation alone may yield a higher coefficient of determination than other moisture variables. Thus, biweekly precipitation totals were also included as independent variables.

Quadratic Functions

The generalized form of the quadratic function used in the analysis was as shown below.

$$\hat{Y} = a + b_i x_i + c_i x_i^2 + d_{ij} x_i x_j$$

where

$\hat{Y}$ = deviations from expected corn yield,

a = a constant,

x_i = monthly values of the moisture index, and

$x_i x_j$ = interaction terms between monthly index values,

$i = 1, \ldots, 4$, and $j = 1, \ldots, 4$, for all $i \neq j$.

The independent variables were as follows:

x_1 = May moisture conditions,

x_2 = June moisture conditions,

x_3 = July moisture conditions, and

x_4 = August moisture conditions.

This quadratic equation was used to analyze the moisture-corn-yield relationship in the West Tennessee study area.[1]

Area Analysis

The quadratic equation when applied to the entire area of West Tennessee provided a relatively good explanation of the corn yield variation during the period of the study. The fitted equation was as shown below.

$$\hat{Y} = 2.04 + \underset{(1.50)}{6.44}x_1 - \underset{(1.03)}{2.69}x_1^2 - \underset{(0.72)}{4.02}x_2 +^{*} \underset{(1.99)}{1.48}x_2^2 - \underset{(1.58)}{6.21}x_3$$

$$- \underset{(0.40)}{0.69}x_3^2 +^{*} \underset{(2.64)}{4.76}x_4 - \underset{(0.62)}{0.91}x_4^2 - \underset{(1.37)}{10.38}x_1x_2 +^{*} \underset{(3.07)}{23.88}x_1x_3$$

$$-^{*} \underset{(2.30)}{8.42}x_1x_4 -^{*} \underset{(2.76)}{22.05}x_2x_3 + \underset{(1.33)}{6.12}x_2x_4 + \underset{(0.81)}{1.52}x_3x_4$$

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[1] For a detailed discussion of quadratic equation production functions see Heady and Dillon (8).

where

$\hat{Y}$ = deviation from expected corn yield,

x_1 = Palmer's Drought Index for May,

x_2 = Palmer's Drought Index for June,

x_3 = Palmer's Drought Index for July,

x_4 = Palmer's Drought Index for August,

x_i^2 = squared values of Palmer's Drought Index for each of the months, where i = 1, ..., 4, and

$x_i x_j$ = interaction terms, where i = 1, ..., 4, and j = 1, ..., 4, for all $i \neq j$.

The t-values for each of the regression coefficients were shown in parentheses beneath each coefficient. Those coefficients which were statistically significant at the 0.05 probability level were indicated with an asterisk. Means and standard deviations of the variables are shown in Appendix Table 11.

The coefficient of determination, R^2, for the area model was 0.85. This indicated that about 85 percent of the variation in corn yield was explained by this equation. Thus, this model was seen to provide a relatively good explanation of the observed corn yield variation for the area during the period of the study.

Marginal physical products with respect to each of the critical months were as shown in Table 3. The magnitude of the marginal physical product in all months except June declined as the Index increased from -4.00 to 4.00 which depicted a movement from extreme drouth to extreme wet conditions.

TABLE 3

MARGINAL PHYSICAL PRODUCTS OF CORN IN RESPONSE TO CHANGES IN PALMER'S DROUGHT INDEX, WEST TENNESSEE, MAY-AUGUST, 1949-1969

Palmer's Drought Index	May x_1	June x_2	July x_3	August x_4
		(Bushels)		
-4.00	31.09	-26.34	9.38	8.88
-3.00	25.71	-23.38	8.00	7.06
-2.00	20.33	-20.42	6.62	5.24
-1.00	14.95	-17.46	5.24	3.42
0.00	9.59	-14.50	3.86	1.60
1.00	4.19	-11.54	2.48	-0.22
2.00	-1.19	-8.50	1.10	-2.04
3.00	-6.57	-5.62	-0.28	-3.86
4.00	-11.95	-2.66	-1.66	-5.68

The marginal physical products were computed by taking the first partial derivative of the complete equation with respect to variables for each month. Values thus computed were found to be reasonable for all months except June. For June, the marginal physical product increased over the full range of moisture conditions. Moreover, the marginal product was a negative value throughout which meant that the total product curve was declining as the amount of moisture was increasing from very dry to very wet. In spite of the fact that the coefficients for June were statistically significant, there appears to be no rational justification for the negative signs.

Optimal moisture conditions were observed during both May and July. This occurred at the point where the value of the marginal physical product became negative. In the case of May, optimum conditions appeared to be at near-normal moisture levels. This was evidenced by the negative values of marginal product when the index rose beyond 1.00. In July, optimum moisture level was at wetter than normal conditions. Thus, slightly wetter than normal conditions during July were found to be conducive to higher than expected corn yield. The largest incremental changes were observed for May and June.

Due to the indirect link between precipitation and Palmer's Drought Index and the unavailability of cost data, no attempt was made to determine the economic optimum index value.

Analysis with Two-Week Precipitation Totals

In order to examine the response of corn yield to precipitation separate equations were used which contained precipitation totals by

two-week periods as independent variables. The complete equation was as shown below.

$$\hat{Y} = -8.74 - \underset{(0.75)}{0.36x_{11}} + \underset{(2.80)}{^{*}0.13x_{11}^{2}} + \underset{(2.06)}{^{*}1.10x_{12}} - \underset{(2.05)}{^{*}0.16x_{12}^{2}}$$

$$- \underset{(1.09)}{0.57x_{21}} + \underset{(1.58)}{0.12x_{21}^{2}} + \underset{(2.41)}{^{*}1.30x_{22}} - \underset{(1.86)}{^{*}0.18x_{22}^{2}} + \underset{(6.20)}{^{*}2.50x_{31}}$$

$$- \underset{(2.74)}{^{*}0.12x_{31}^{2}} + \underset{(3.09()}{^{*}0.73x_{32}} - \underset{(2.97)}{^{*}0.58x_{32}^{2}} - \underset{(1.57)}{1.05x_{41}} + \underset{(1.32)}{0.17x_{41}^{2}}$$

$$+ \underset{(1.66)}{0.89x_{42}} - \underset{(1.38)}{0.11x_{42}^{2}}$$

where

$\hat{Y}$ = deviations from expected corn yield, and

x_{ij} = precipitation by two-week period, i = month, and

j = the period of the month, i = 1, ..., 4, and

j = 1,2.

T-values are shown in parentheses beneath each of the coefficients. Those variables which were statistically significant at the 0.05 probability level were indicated by an asterisk. Means and standard deviations of the variables are shown in Appendix Table 12. The coefficient of determination for the fitted equation was 0.38, which meant that the equation explained about 38 percent of the yield variation.

A comparison of this equation with the one containing Palmer's Drought Index values as independent variables showed, on the basis of the coefficients of determination, that the precipitation equation

accounted for roughly one-half as much variation as was explained by the equation containing the monthly moisture index values. However, application of the results differ significantly. Since there is no easily identifiable and quantifiable relationship between inches of precipitation during a month and Palmer's Drought Index during the same month, the effects on corn yield of incremental changes in inches of precipitation operating through the Index are not easily discernable. On the other hand, a more straightforward relationship existed between inches of precipitation during the two-week periods and corn yield. Consequently, the marginal contribution to corn yield of incremental changes in precipitation can be computed and used as a basis for an economic evaluation of additional precipitation during specified periods of time. Marginal physical products of additional inches of rainfall by two-week periods are shown in Table 4.

For the first period in May, June, and August, marginal physical product rose as inches of precipitation varied from 0.00 to 4.00 inches. During each of these periods, marginal physical product was negative at low precipitation totals and increased to become positive at higher precipitation totals. These results indicated that total physical product decreased, with other periods held at their mean values, as precipitation increased to about 2.00 inches. At that point total product began to rise. There was no reason to expect these irrational results during these particular periods.

For all other two-week periods, marginal physical product declined and in most instances became negative as precipitation varied from low

TABLE 4

MARGINAL PHYSICAL PRODUCT OF CORN WITH ADDITIONAL INCHES OF PRECIPITATION, WEST TENNESSEE, 1949-1969

Precipitation	Time Periods							
	May		June		July		August	
	1	2	1	2	1	2	1	2
(Inches)	(Bushels)							
0.00	-0.36	1.10	-0.57	1.30	2.50	0.73	-1.05	0.89
1.00	-0.10	0.78	-0.33	0.94	2.26	-0.43	-0.71	0.67
2.00	0.16	0.46	-0.09	0.58	2.02	-1.59	-0.37	0.45
3.00	0.42	0.14	0.15	0.22	1.78	-2.75	-0.03	0.23
4.00	0.68	-0.18	0.39	-0.14	1.54	-3.91	0.31	0.01

to high. This indicated that total physical product increased as precipitation increased to about 3.00 inches, then began to decline at higher precipitation levels. Thus, during these periods, precipitation appeared to be a limiting factor in corn production.

The largest marginal contribution of an extra inch of precipitation to corn yield was found in the first two-week period in July. For example, the marginal physical product for the first period in July, evaluated at the 1.00 inch level and with precipitation for other periods held at their means, was 2.26 bushels. Thus, an extra inch of precipitation would have increased corn yield by 2.26 bushels per acre. This was the only period in which an increase in precipitation throughout the scale shown in Table 4 would have made a significant positive contribution to corn yield. Even at the 4.00 inch level, the marginal contribution of an extra inch of precipitation was 1.54 bushels of corn per acre. This period appeared to be the most critical, insofar as precipitation was concerned, in corn production in the West Tennessee area.

The marginal contributions of extra inches of precipitation takes on added significance when actual corn yield variation is taken into account. Averaging annual corn yields over counties greatly reduced the range of yield variation and consequently underestimated the marginal response at higher levels of production. Thus, the findings of this study provide no basis for estimating corn yield response to weather variables at high levels of management and production which prevails on many individual farms. Insofar as intentional modifications in precipitation totals may be made, all producers in an area would benefit by

adding incremental units of moisture up to the point where the cost of such increments just equals the value of the marginal product resulting from the increase in moisture.

The results of the precipitation equation agreed with those from the equation containing Palmer's Drought Index. The conclusion was that regression equations containing the Index provided a better fit to the data than did the equation containing inches of precipitation during the two-week periods. The difficulty with the drouth Index measurement lay in the inability to interpret yield response in terms of single weather variables. Since the drouth Index was a composite of many variables it was not possible to draw inferences regarding the effects of single variables such as precipitation or temperature.

CHAPTER V

PRECIPITATION PROBABILITIES AND CORN PRODUCTION DECISIONS

> Accurate, long-range forecasts would be of great value in the planning of production practices. Ideally, forecasts would foretell when precipitation was going to occur and in what quantities. (12, p. 3)

If reliable forecasts were available, producers would have useful information for advance planning of farming operations. Producers could decide what crop to produce, the variety to plant, the ideal planting time, whether or not to purchase irrigation equipment, the timeliness and the magnitude of irrigation water applications, and the proper time to harvest the crop. Thus, managerial decisions would be greatly simplified.

Unfortunately, accurate forecasts are not available to producers. Therefore, managers must base their decisions on as much knowledge as they can obtain relative to the weather in general and to the quantity and distribution of precipitation in particular.

Short-range weather forecasts are made, and in many instances are quite accurate. They serve as bases for many managerial decisions, expecially in relation to day-to-day operations. Forecasts and weather reports made presently are seldom made for more than a five day period.

What producers need, however, are forecasts for longer periods of time that are dependable and upon which production decisions may be based. Presently, little basis exists for making such forecasts on other than historical data. This study did not attempt to make weather

forecasts but did estimate probable occurrence of precipitation. This was done in an attempt to convert uncertainties into risks.

McQuigg and Doll (7, p. 33) reported that:

> Identifying weather variables and deriving their frequency distribution changes uncertainties into risks. That is, the manager gains knowledge of the probable occurrences of weather events about which he either has limited knowledge or no knowledge. Over time, the distribution can be used to determine expected profits or losses. Within a single growing season or production period, the manager does not know what will occur and hence still faces an uncertain situation. In this case, he can use the frequency distribution to evaluate the odds for or against a particular alternative. Thus, while he does not know what will occur, he knows what is likely to occur or likely not to occur. Once he knows the probability of success for a managerial decision he can evaluate for himself whether or not to undertake the action.

It is not essential that precipitation be perfectly forecast for an estimating model to be of value to the producer or to the policy maker. Probability distributions of expected precipitation can be computed from records for almost any geographical area. Managers may then be able, through these distributions, to make better informed production decisions.

Yield Estimation

On a broad scale, precipitation probabilities may assist policy makers and planners in decision making with respect to intentional weather modification. They may also be beneficial in making in-season adjustments in annual crop yield estimates. Yield estimates for selected areas could be updated throughout the growing season based on moisture availability, the potential moisture demand, and precipitation probabilities for subsequent months.

Weather Uncertainty and Management Decisions

With computed precipitation probabilities, producers may select, for example, fertilization rates based on predetermined probabilities of given levels of precipitation.

Availability of weather crop yield response data and precipitation probabilities do not lessen the possibility of weather induced yield variations. They do, however, allow managers to operate at a predetermined risk level relative to weather. Such knowledge does not remove risks but does allow them to make more accurate assessments of the risks which may result from variations in soil moisture conditions.

For example, given probability estimates of precipitation, managers in a "relatively favorable" capital position might select strategies involving expectations of an "adequate" quantity of precipitation during the critical period in the development of the corn plant. They would then fertilize according to recommendations for a high precipitation level even though there may be only say a 50 percent probability that the expected quantity of precipitation will occur.

On the other hand, managers in "less favorable" capital positions may be less willing to assume the risks involved in heavy fertilizer application. If sufficient precipitation occurs, yields would be less than if the rate of fertilization had been higher. Yet, if insufficient precipitation occurs, managers would minimize losses. Managers in this case might choose to select a strategy based on say an 80 percent probability level.

In this chapter a model was developed to determine the probability of occurrence of various amounts of precipitation during each month of the year. Long-term estimates were made which were based on the probability of occurrence of selected levels of precipitation. Probabilities were computed by the use of an incomplete gamma function.[1] Computations were based on 21 years of data for weather reporting stations in each of the 14 counties included in this study.

Of a similar procedure which he used in Texas, Bilbro (12, p. 7) pointed out that:

> Long-term weather records provide data on certain aspects and features of the climate in the past. Certain calculations made on such data make it possible to estimate or predict the probability of occurrence (odds) of a given feature in the future.

The procedure used to compute the precipitation probabilities for this study were similar to those used by Bilbro.

Moisture Requirements and Availabilities

Values arising from intermediate steps in the computations of Palmer's Drought Index were used to develop a model to evaluate the probability of abnormal weather conditions during a growing season. For a given location, the sum of potential evapotranspiration, PE, and available soil moisture at the beginning of the month, SP, provided an estimate of the quantity of water required to meet the moisture requirements of the corn crop during the subsequent month. Estimates of potential evapotranspiration were based on long-term averages of monthly

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[1]The computer program used to make the necessary computations was obtained from the National Climatic Center in Asheville, North Carolina.

evapotranspiration. The quantity of soil moisture available at the beginning of each month was ascertained by an accounting process which was a part of Palmer's computational procedure. It was simply the amount of moisture remaining in the two layers of the soil at the end of the previous month.

Thus, potential moisture requirement, PMR, was defined as the monthly potential evapotranspiration plus the potential soil recharge, PR. Potential recharge was the difference between field capacity, 4.00 inches in West Tennessee, and the quantity of moisture in the soil at the beginning of the month. This relationship may be written as follows:

(1) $$PR = FC - SP$$

where

PR = potential recharge,

FC = field capacity of the soil, 4.00 inches, and

SP = moisture available in the soil at the beginning of the month.

Potential moisture requirement may be expressed by the following equation.

(2) $$PMR = PE + PR$$

where

PMR = potential moisture requirement,

PE = potential evapotranspiration, and

PR = potential recharge.

Values used in the two equations were available from the Palmer's Drought Index computations.

Given these data on potential moisture requirement, the probability of precipitation occurrence in quantities sufficient to fulfill the potential moisture requirement for any given area can be ascertained by reference to a precipitation probability distribution table for the same area for the months being considered. This information permits estimates of the chances of occurrence of abnormal moisture conditions.

Probability distributations were prepared for each county included in this study. As shown in Appendix Table 10, producers in Haywood County could determine the probability of occurrence of various precipitation levels during any month of the year. These data may be beneficial to the individual producer in the county in planning his corn growing operations as well as to the planner and the policy maker in making estimates of the corn yield.

The model was also used to predict month-to-month changes in moisture conditions. Producers, through the use of this model, can predict the chances of a "bettering" or a "worsening" of drouth conditions for any given location on a monthly basis. Assume, for example, a computed index value of -1.80 at the end of June in Haywood County. This would indicate a slight drouth. An estimate of the probable change in drouth conditions can be made by comparing the potential moisture requirement for July with the probability of occurrence of that quantity of precipitation, plus the moisture available in the soil at the beginning of the month. Assume that the quantity of moisture at the beginning

of July was 1.50 inches, and that potential evapotranspiration was 5.00 inches. The potential moisture requirement would be 5.00 + 4.00 - 1.50 or 7.50 inches of moisture. The probability distribution indicated that the chances of occurrence of the required quantity of precipitation to meet the potential requirement was about 30 percent. Therefore, the chances would be about 3 in 10 that precipitation in July would be sufficient to eliminate the slight drouth conditions which existed at the end of June and to provide sufficient moisture to satisfy the potential July requirement. Producers would thus expect the drouth conditions to become worse in July. In view of this anticipated change in soil moisture conditions, planners would lower their estimates of the corn yield expected in Haywood County.

Moisture Anomaly Prediction Model

In order to test the model developed in this chapter and to exhibit its usefulness, a detailed application was made of it with respect to Haywood County, for selected years during the period from 1949 through 1969. This county was arbitrarily selected from the 14 counties comprising the study area.

Deviations from expected average corn yields were used to select "good" and "bad" years. "Good" years were those in which actual yield was 5.0 bushels or more above expected yield. "Bad" years were those in which actual yield was 3.0 bushels or more below the expected yield. Table 5 shows the actual yield, computed yield, and deviations for Haywood County for the years 1949 through 1969.

TABLE 5

DEVIATIONS OF ACTUAL FROM EXPECTED CORN YIELD,
HAYWOOD COUNTY, TENNESSEE, 1949-1969

Year	Expected Yield	Actual Yield	Deviations
	(Bushels)	(Bushels)	(Bushels)
1949	16.1	21.5	5.4
1950	18.0	25.0	7.0
1951	19.8	25.5	5.7
1952	21.7	17.5	-4.2
1953	23.6	23.0	-0.6
1954	25.4	12.0	-13.4
1955	27.3	27.0	-0.3
1956	29.2	21.5	-7.7
1957	31.0	24.0	-7.0
1958	32.9	33.5	0.6
1959	34.7	34.5	-0.2
1960	36.6	36.0	-0.6
1961	38.4	45.0	6.6
1962	40.3	42.0	1.6
1963	42.2	51.0	8.8
1964	44.0	45.0	1.0
1965	45.9	53.0	7.1
1966	47.8	44.0	-3.8
1967	49.6	64.0	14.4
1968	51.5	46.0	-5.5
1969	53.3	42.0	-11.3

Tables 6 and 7 show the value of Palmer's Drought Index for selected months during both the "good" and the "bad" years. The months of May through August were selected because the crop was planted, grown, and harvested, normally, during these four months.

During six of the seven "bad" years, the value of the Index for both June and July was negative. Also, during all the years in which drouth conditions occurred, the Index indicated a worsening of drouth conditions from May through August. A worsening of drouth conditions occurred as the Index took on successively larger negative values. Only in 1957 did conditions become wetter during the period of time in which the crop was actively growing.

In contrast to the years in which corn yield in Haywood County was below that expected with normal moisture conditions, Table 8 shows the value of the Index for selected months during six years when average yield was higher than expected with normal conditions. With the exceptions of 1963 and 1967, months in which the corn plants were growing moisture conditions were either normal or slightly wetter than normal. This lends support to the hypothesis that peak corn yields were expected with normal or near-normal moisture conditions, especially during June and July.

Predictability of the Model

A comparison of the potential moisture demand with a predetermined probability of precipitation occurrence was made for those years which were classified both as "good" and "bad". This comparison was

TABLE 6

"GOOD" YEARS--YEARS WITH HIGHEST POSITIVE DEVIATIONS FROM EXPECTED CORN YIELD, HAYWOOD COUNTY, TENNESSEE, 1949-1969

Year	Deviations from Expected Yield	Palmer's Drought Index			
		May	June	July	August
1949	5.4	0.78	2.54	1.84	1.10
1950	7.0	1.57	1.84	2.53	3.85
1951	5.7	1.19	1.87	1.79	1.06
1963	8.8	-2.23	-1.75	-1.23	-1.17
1965	7.1	-0.43	-0.94	-0.87	-1.41
1967	14.4	0.96	1.44	2.33	-0.07

TABLE 7

"BAD" YEARS--YEARS WITH HIGHEST NEGATIVE DEVIATIONS FROM EXPECTED CORN YIELD, HAYWOOD COUNTY, TENNESSEE, 1949-1969

Year	Deviations from Expected Yield	Palmer's Drought Index			
		May	June	July	August
1952	-4.2	-0.98	-1.97	-2.50	0.73
1954	-13.4	-0.88	-1.15	-2.45	-3.07
1956	-7.7	-1.09	-0.86	-2.44	-3.02
1957	-7.0	1.19	3.41	4.45	5.38
1966	-3.8	-1.78	-2.40	-3.28	-1.96
1968	-5.5	1.33	-0.15	-0.86	-2.05
1969	-11.3	-1.15	-2.41	-3.26	-3.42

TABLE 8

PREDICTION ACCURACY OF THE ANOMALY PREDICTION MODEL WITH AN 80 PERCENT PROBABILITY LEVEL FOR SELECTED COUNTIES IN WEST TENNESSEE, 1949-1969

County	All Months	May-August
	(percent)	(percent)
Hardeman	.54	.59
Haywood	.55	.64
Tipton	.55	.62
Carroll	.51	.60
Madison	.56	.62
Weakley	.51	.63
Shelby	.51	.60
Gibson	.56	.65
Fayette	.55	.64
Dyer	.54	.60
Henry	.51	.60
Hardin	.57	.59
McNairy	.51	.64
Obion	.51	.54
All Counties	.53	.61

made to test the effectiveness of the predictions. The model was designed to predict changes in soil moisture conditions based on existing conditions and the probability of occurrence of precipitation for the following month.

If potential moisture requirement, for the years shown in Tables 6 and 7, exceeded the potential availability, the moisture index was expected to decline. If the potential moisture availability exceeded the potential requirement the index was expected to increase.

Using a probability level of 80 percent, the model predicted changes in monthly moisture conditions during the "good" years in 40 of the 72 month period shown in Table 6. This was an accuracy rate of 56 percent. During the same time period, for the months of May, June, July, and August, changes were accurately predicted in 14 of 24 months, for a 58 percent accuracy rate. Considering all months of the seven "bad" years, changes were accurately predicted in 44 of 84 months, for a 52 percent rate of accuracy. When the May through August period for the "bad" years was considered, changes were accurately predicted in 17 of 28 months for a rate of 61 percent.

The model as applied to Haywood County appeared to provide only a fair predictor of changes in monthly moisture conditions. However, the model proved to predict changes considerably better during the period of May through August.

In this illustration, an 80 percent precipitation probability level was selected. A relatively high level was selected so as to be reasonably certain that not less than the predicted level of

precipitation would occur. This resulted in a bias in the predictions toward drouth conditions. There was a tendency to predict downward movements in the moisture Index more often than upward movements.

For the entire study area, as shown in Table 8, page 51, the model accurately predicted changes in 53 percent of the months. When the May through August period was considered, the model exhibited a prediction accuracy of 61 percent. The accuracy of the model for each county was better for the May through August period than when all months of the year were included.

CHAPTER VI

SUMMARY AND CONCLUSIONS

Summary

The findings of this study are applicable to agricultural production problems arising from the uncertainty of weather. An analysis was made of the effects of varying moisture and precipitation levels on corn yields for 14 selected counties in West Tennessee. Estimates were made of the direction and the magnitude of these effects. The basic assumption underlying the study was that abnormal moisture conditions during the growing season affected corn yield adversely. It was hypothesized that too much as well as too little soil moisture contributed to yield reductions.

Average yield during the 21 year period covered by the study varied from a low of 32.48 bushels per acre in Hardeman County to a high of 47.19 bushels in Obion County. A relatively clear differentiation existed between average yields in the Northern and Southern portions of the study area. Yields were decidedly higher in the Northern half of the study area. Average yields for the entire area increased at an annual rate of about 1.60 bushels per acre. The highest rate of increase of 2.19 bushels per acre was in Obion County and the lowest rate of 1.28 bushels was in McNairy and Shelby Counties.

Palmer's Drought Index was used to represent soil moisture conditions. This method took into account various climatological

phenomena including temperature, precipitation, evapotranspiration, length of day, and distance and angle from the sun, in calculating the moisture conditions at any given time and location. The Index was computed independently of both technology and yield data. Computations were made on a monthly basis for each county in the study area. Climatological data from one reporting station in each county were used. These data were assumed to be representative of the county as a whole.

Two regression analyses were made. One included Palmer's Drought Index values as independent variables and the other included two-week precipitation totals as independent variables. The quadratic equation using Palmer's Drought Index when applied to the data for the entire area provided a relatively good explanation of corn yield variation during the study period. The coefficient of determination indicated that the equation explained about 85 percent of the variation in yield.

Marginal physical products computed for the fitted equation declined as the index values increased, in all months except June. In June, the marginal physical products were negative at low Index values and increased throughout the range of Index values. The coefficients for the June variables were found to be statistically significant but, nevertheless meaningless.

Optimum levels of Palmer's Drought Index were observed at near-normal conditions in May and at slightly wetter than normal conditions in July. The largest changes in corn yield resulting from incremental changes in Palmer's Drought Index were observed for July. Thus, July was seen as the most critical month in corn production in West Tennessee.

The regression equation with precipitation totals as independent variables accounted for about 38 percent of the variation in corn yield.

For the first two-week period in May, June, and August, marginal physical product rose as units of precipitation increased from 0.00 to 4.00 inches.

Marginal physical product generally was negative at low precipitation levels and became positive at higher levels. For the other periods, marginal physical product declined and became negative in most instances as precipitation increased from 0.00 to 4.00 inches. The largest marginal contribution, 2.50 bushels, from an extra inch of precipitation was found in the first period in July.

The marginal contributions of extra inches of precipitation takes on added significance when actual corn yield variation is taken into account. Averaging annual corn yields over counties greatly reduced the range of yield variation and consequently underestimated the marginal response at higher levels of production. The effects of the moisture Index and of precipitation would have been more pronounced had actual yield variations been used rather than restricting them to average yields. Insofar as intentional modifications in precipitation totals may be made, producers would benefit by adding incremental units of moisture up to the point where the cost of such increments just equals the value of the marginal product resulting from the increase in moisture.

The difficulty with the Drought Index lay in the inability to interpret yield responses in terms of single weather variables. Since the Index was a composite of many variables it was not possible to draw

inferences regarding the effects of single variables such as precipitation or temperature.

A moisture anomaly prediction model was developed using data generated in the computations of the moisture Index and precipitation probability distributions to predict changes in monthly soil moisture conditions. Potential moisture requirement and potential moisture availability were computed. If the potential requirement exceeded the potential availability, conditions were expected to become drier, with a corresponding decrease in the magnitude of the Index. If potential availability exceeded potential requirment, conditions were expected to become wetter, with a corresponding increase in the magnitude of the Index. Potential occurrences were then compared to actual precipitation and the subsequent change in the Index to determine the accuracy of the prediction model for the 21 year period studied. With all months considered, the model for all counties combined provided accurate predictions about 53 percent of the time at the 80 percent level. When the critical months of May, June, July, and August were considered, the predictive accuracy rose to about 61 percent.

Conclusions

The analysis showed the quantative response of corn yield to changes in monthly moisture conditions. Application of the findings of this study may be made in two general ways. First, producers may be able to evaluate their need for irrigation in growing corn in West Tennessee. Second, the results may provide a framework for economic analysis of intentional weather modification. Assigning prices to

the value of the marginal products computed herein would provide a part of the information necessary to determine the economic optimal moisture conditions for any given month during the corn growing season. Optimal conditions might then be achieved either by irrigation or by intentional weather modification.

There is very little a producer can do during the growing season in response to estimates of forthcoming drouth or to an expected worsening of existing drouth conditions. However, for longer periods of time, producers can use the results of the moisture prediction model to augment their decision making processes. This information can be useful in selecting crops and crop varieties to produce, in planning fertilization rates, and in evaluating the need for and the timeliness of irrigation water application. These predictions can also be used by governmental agencies whose concern is the estimation of crop yields in general and corn yields in particular. The predictions would allow in-season adjustments in yield estimates to be made on the basis of anticipated changes in the moisture conditions for the remainder of the growing season.

There was a bias in the predictability of the model toward drouth, which might be beneficial since drouth was found to be more detrimental to corn production than excessively wet conditions.

This model in conjunction with condition reports and other information available to crop yield estimators would lend valuable assistance in increasing the accuracy of yield estimation. More accurate estimates are desirable from a number of viewpoints.

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APPENDIXES

APPENDIX A

TABLE 9

AVERAGE CORN YIELD AND NUMBER OF ACRES BY COUNTY,
WEST TENNESSEE, 1949-1969

Year	Obion		Dyer		Tipton		Shelby		Fayette		Hardeman		McNairy	
	Acres	Bu.	Acres	Bu.	Acres	Bu.	Acres	Bu.	Acres	Bu.	Acres	Bu.	Acres	Bu.
1949	65,000	33.0	44,800	29.0	34,000	24.0	41,000	22.0	41,500	20.0	31,900	21.0	33,500	21.5
1950	66,000	33.0	46,000	30.5	35,000	25.0	40,000	23.0	43,200	23.0	32,000	24.0	36,000	25.0
1951	56,000	33.0	42,000	28.7	31,000	25.0	36,000	22.0	39,300	23.5	29,000	24.0	34,000	25.0
1952	55,000	29.5	40,900	24.5	32,200	20.5	37,000	20.5	39,300	17.0	29,000	19.5	33,000	18.0
1953	52,500	34.5	34,500	30.0	29,800	25.5	32,500	34.5	38,000	23.0	28,500	24.5	31,000	22.0
1954	59,500	24.5	36,900	19.0	39,000	17.0	37,600	14.0	46,500	12.5	33,500	13.0	35,000	23.5
1955	51,800	42.0	32,500	39.0	33,600	34.0	31,000	27.0	41,400	26.0	30,000	26.5	32,600	32.0
1956	49,500	39.0	32,600	35.0	31,600	28.5	31,200	23.5	42,000	21.5	30,800	22.5	33,100	27.0
1957	37,400	31.4	27,900	33.9	25,500	32.0	24,400	28.0	35,100	26.0	24,400	27.0	26,600	25.9
1958	39,500	44.5	26,100	39.5	25,000	36.0	21,500	32.0	32,700	32.5	28,400	31.5	33,500	31.0
1959	44,000	49.5	27,700	43.5	26,000	42.0	20,500	34.0	33,400	35.0	29,200	34.0	36,900	30.5
1960	44,800	48.0	28,700	45.0	26,600	41.0	20,900	34.0	32,600	33.5	28,400	33.5	35,800	33.5
1961	34,200	52.0	20,500	55.0	19,700	44.0	13,600	41.0	26,800	39.0	20,600	40.0	26,100	43.0
1962	35,500	54.0	22,200	47.0	20,000	42.0	12,600	37.0	25,600	35.0	17,300	36.0	22,000	38.0
1963	37,800	65.0	23,100	59.0	20,200	48.0	12,600	47.0	26,800	47.0	16,600	48.0	21,900	47.0
1964	41,900	60.0	27,600	53.0	22,800	42.0	10,500	36.0	25,700	43.0	16,500	47.0	21,700	45.0
1965	40,900	65.0	22,900	62.0	20,300	41.0	9,700	39.0	25,500	50.0	16,000	46.0	20,100	48.0
1966	34,600	57.0	19,800	57.0	16,000	45.0	7,000	31.0	26,300	41.0	15,000	33.0	19,500	35.0
1967	35,300	71.0	19,500	76.0	15,700	62.0	7,500	58.0	28,400	63.0	16,300	53.0	19,400	52.0
1968	33,800	71.0	18,200	74.0	14,100	40.0	6,100	38.0	24,100	46.0	13,600	43.0	17,600	42.0
1969	31,100	69.0	19,700	63.0	12,000	32.0	5,100	34.0	24,100	32.0	14,500	29.0	17,200	32.0

TABLE 9 (continued)

Year	Madison		Haywood		Gibson		Carroll		Weakley		Henry		Hardin	
	Acres	Bu.	Acres	Bu.	Acres	Bu.	Acres	Bu.	Acres	Bu.	Acres	Bu.	Acres	Bu.
1949	32,600	24.0	39,500	21.5	62,000	27.5	35,000	24.5	70,000	27.0	37,400	27.5	33,300	24.5
1950	36,000	28.0	40,700	25.0	63,000	31.0	37,000	28.0	71,000	31.0	38,000	32.0	34,200	27.0
1951	33,000	27.5	37,400	25.5	61,000	30.5	36,500	28.0	68,000	30.0	38,000	31.0	27,000	33.0
1952	31,500	18.0	36,500	17.5	58,000	23.0	36,300	19.0	66,500	22.5	38,700	22.5	27,000	19.5
1953	33,000	25.0	33,200	23.0	52,500	25.5	19,700	26.0	63,500	27.0	36,200	26.0	32,000	25.0
1954	40,500	14.5	39,500	12.0	65,500	16.0	22,500	14.0	71,000	16.5	41,500	19.0	36,000	18.5
1955	35,900	31.0	34,400	27.0	52,500	37.0	38,300	29.0	59,300	33.5	35,100	33.5	34,300	29.0
1956	36,400	25.5	32,900	21.5	52,600	30.5	40,100	26.5	58,100	30.5	34,400	29.0	32,600	29.5
1957	28,600	27.9	25,000	24.0	38,500	29.8	30,600	29.5	37,000	29.0	22,700	31.8	26,800	27.7
1958	35,300	35.5	24,900	33.5	45,300	35.0	36,400	35.0	45,900	35.5	27,400	38.0	27,600	31.5
1959	36,100	36.5	25,700	34.5	46,500	36.5	37,800	36.5	49,200	36.5	29,700	38.5	29,500	29.5
1960	35,300	38.0	25,300	36.0	43,700	37.5	36,200	36.5	45,800	37.5	27,500	38.5	28,500	29.5
1961	27,900	46.0	20,000	45.0	34,300	41.0	25,200	38.0	31,600	41.0	20,100	47.0	21,800	41.0
1962	24,700	40.0	18,000	42.0	32,100	40.0	21,400	40.0	27,200	44.0	17,300	41.0	20,700	35.0
1963	24,800	49.0	19,800	51.0	33,800	53.0	20,800	50.0	27,700	55.0	17,700	56.0	20,300	48.0
1964	25,600	47.0	20,000	45.0	35,600	51.0	20,600	49.0	27,700	50.0	17,500	49.0	19,700	46.0
1965	23,800	53.0	18,000	53.0	30,700	56.0	19,700	52.0	24,300	57.0	16,800	54.0	16,400	45.0
1966	22,100	43.0	18,800	44.0	31,100	54.0	17,800	38.0	25,500	50.0	17,100	46.0	16,300	40.0
1967	24,500	56.0	20,000	64.0	31,600	67.0	18,300	56.0	26,900	67.0	18,100	61.0	15,500	46.0
1968	20,500	43.0	18,600	46.0	28,700	54.0	15,100	43.0	23,500	51.0	15,300	50.0	12,800	32.0
1969	17,600	31.0	18,000	42.0	26,900	46.0	15,700	45.0	23,300	57.0	14,800	54.0	10,700	27.0

APPENDIX B

COMPUTATIONAL EQUATIONS FOR PALMER'S DROUGHT INDEX

(1) $L_s = S'_s$, or (PE - P), whichever is smaller, and

(2) $L_u = (PE - P - L_s)\ S'_u/AWC$, and $L_u - S'_u$

where, L_s = moisture loss from surface layer of the soil,

S'_s = available moisture stored in the surface layer of soil at the beginning of the month,

PE = potential evapotranspiration for the month,

P = precipitation for the month,

L_u = water loss from the underlying layer of soil,

S'_u = available moisture stored in the underlying layer of the soil at the beginning of the month, and

AWC = combined available capacity of both layers of the soil.

Potential evapotranspiration, PE, is estimated by Thornthwaite's potential evapotranspiration term.

(3) PR = AWC - S'

where, S' = the amount of available moisture in both soil layers,

PR = potential recharge.

(4) $PL = PL_s + PL_u$

where, PL = potential loss,

PL_s = potential loss from the surface layer, and

PL_u = potential loss from the underlying layer.

(5) PRO = AWC - PR = S'

(6) $\alpha = \overline{ET}/\overline{PE}$

where, α = coefficient of evapotranspiration,

$\overline{ET}$ = long-term ET, and

$\overline{PE}$ = long-term mean potential ET for a calender month.

(7) $\beta = \overline{R}/\overline{PR}$

where, β = coefficient of recharge,

$\overline{R}$ = long-term mean recharge, and

$\overline{PR}$ = long-term mean potential recharge.

(8) $\gamma = \overline{RO}/\overline{PRO} = \overline{RO}/\overline{S'}$

where, γ = coefficient of runoff,

$\overline{RO}$ = long-term mean runoff,

$\overline{PRO}$ = long-term mean potential runoff.

(9) $\delta = \overline{L}/\overline{PL}$

where, δ = coefficient of loss,

$\overline{L}$ = long-term mean loss, and

$\overline{PL}$ = long-term mean potential loss.

(10) $\hat{ET} = \alpha PE$

where, $\hat{ET}$ = expected value of $\hat{ET}$,

$\hat{R} = \beta PR$

where, $\hat{R}$ = expected value of R

$\hat{RO} = \gamma PRO$

where, $\hat{RO}$ = expected value of RO

$\hat{L} = \delta PL$

where, $\hat{L}$ = expected value of L

$\hat{P} = \hat{ET} + \hat{R} + \hat{RO} - \hat{L}$

(11) $d = P - \hat{P}$

where, d = departure from expected precipitation.

(12) $Z = Kd$

where, Z = monthly moisture anomaly, and

K = a weighting factor.

(13) $K = (\overline{PE} + \overline{R}) / (\overline{P} - \overline{L})$

(14) $X_i = \sum_{t=1}^{i} Z_t / (0.309t + 2.691)$

where, X_i = Palmer's Drought Index, i = 1, ..., 12 months.

APPENDIX C

TABLE 10

AMOUNT OF PRECIPITATION EXPECTED IN ONE MONTH WITH SPECIFIED PROBABILITY LEVELS, HAYWOOD COUNTY, TENNESSEE

Month	Mean	Probability 0.05	0.10	0.20	0.30	0.40	0.50	0.60	0.70	0.80	0.90
Jan.	5.32	11.728	9.799	7.746	6.453	5.468	4.642	3.905	3.210	2.513	1.734
Feb.	5.09	10.258	8.759	7.139	6.101	5.296	4.611	3.988	3.388	2.769	2.048
Mar.	5.54	10.657	9.215	7.620	6.582	5.771	5.074	4.437	3.816	3.170	2.405
Apr.	5.58	9.402	8.369	7.220	6.459	5.853	5.321	4.822	4.325	3.789	3.124
May	4.45	9.117	7.751	6.280	5.340	4.615	3.999	3.441	2.906	2.356	1.721
June	3.58	7.548	6.381	5.118	4.313	3.694	3.172	2.701	2.253	1.797	1.279
July	4.45	10.026	8.328	6.530	5.403	4.548	3.835	3.202	2.608	2.017	1.364
Aug.	2.90	8.220	6.421	4.601	3.519	2.740	2.126	1.614	1.169	0.771	0.398
Sep.	3.77	8.763	7.179	5.513	4.475	3.692	3.042	2.466	1.925	1.381	0.748
Oct.	2.45	4.978	4.221	3.405	2.881	2.476	2.129	1.812	1.502	1.174	0.754
Nov.	4.05	8.951	7.473	5.902	4.913	4.159	3.528	2.966	2.435	1.903	1.310
Dec.	4.58	10.014	8.385	6.648	5.551	4.714	4.012	3.384	2.790	2.193	1.523

TABLE 11

MEANS AND STANDARD DEVIATIONS OF MONTHLY VALUES OF PALMER'S DROUGHT INDEX, WEST TENNESSEE, 1949-1969

Month	Mean	Standard Deviation
May	0.54	1.76
June	0.15	1.75
July	0.31	2.01
August	0.32	2.30

TABLE 12

MEANS AND STANDARD DEVIATIONS OF TWO-WEEK PRECIPITATION QUANTITIES, WEST TENNESSEE, 1949-1959

Month	Period	Mean	Standard Deviation
May	1	2.34	1.83
	2	2.22	1.68
June	1	2.10	1.75
	2	1.60	1.46
July	1	2.30	1.80
	2	1.89	1.48
August	1	1.46	1.32
	2	1.73	1.69

VITA

Garey Banks Perkins was born in Vernon, Alabama, on January 24, 1939. He attended elementary schools in Crossville and Vernon, Alabama, and was graduated from Lamar County High School in 1957. The following September he entered Auburn University at Auburn, Alabama. He received a Bachelor of Science degree in agricultural education in 1961 and a Master of Science degree in agricultural economics in 1963.

He served as an officer in The United States Air Force from 1963 to 1966. During 1966 and 1967, he was employed as an Instructor in economics at The University of North Dakota, Grand Forks, North Dakota.

He entered Graduate School at The University of Tennessee in September 1967 and received the Doctor of Philosophy degree with a major in agricultural economics in 1971.

He is a member of Alpha Gamma Rho, Gamma Sigma Delta, Omicron Delta Epsilon, The American Agricultural Economics Association, and The Southern Agricultural Economics Association.

He is a member of the Church of Christ and has served as a Deacon and as a minister in the church.

He is married to the former Banks Prater of Kennedy, Alabama. They have two children, Thomas Gary and Lisa Michele.