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Villalpando-Ibarra, Jose Francisco

MODELING CORN YIELDS AND OPTIMUM NITROGEN RATES UNDER VARIABLE SOIL AND CLIMATIC CONDITIONS IN THE WESTERN PART OF THE EL BAJIO AREA, MEXICO

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Modeling corn yields and optimum N rates under variable soil and climatic conditions in the western part of the El Bajio area, Mexico

by

Jose Francisco Villalpando-Ibarra

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I. INTRODUCTION

Corn is the most important crop in Mexico. About 40% of the crop area is planted with this cereal. In addition, about 90% of the corn area is planted under rainfall conditions which make annual corn production very dependent upon weather conditions. This situation has largely been responsible for the high year-to-year variation in Mexico's corn production. Weather conditions can make the difference between getting good corn production and obtaining self-sufficiency in this crop or having to import corn to make up the deficit. This fact makes it of paramount importance to develop adequate methods to characterize weather and its effects on corn yield.

The effect of weather in agricultural production and field experimentation has long been recognized, and there have been many attempts to evaluate it. Dale and Shaw (1965) have stated that all agricultural research results are dependent upon weather conditions under which the research is performed. To characterize weather and its effect on crop yields, several methods have been developed; these include the use of single meteorological variables such as rainfall and temperature, drought indexes based on different criteria, moisture stress indexes which represent an integration of soil moisture and atmospheric demand, and plant-water status.

Crop yields at a location are not only the result of weather conditions, but also of the composite effect of soil, management, and environmental factors which affect the growth and development of the crop. The influence that all these factors have on crop yield can be approximated using empirical-statistical models. These regression models have been found to be useful tools to use in simulation studies (Kissel et al., 1975). According to them, results from agricultural research may be used in developing crop-yield simulation models. Models previously evaluated can be used, for instance, in simulating the crop response to different levels of fertilizer, tillage practices, etc. using historic weather records. In this way, a large number of "experiments" may be accomplished quickly, which otherwise would take many years of field work. Likewise, simulation of crop yields for a given set of management practices could be performed using weather records. A distribution of yields constructed from the simulation results is a useful tool in decision making for both the farmer and the agricultural planner.

With this in mind, the objectives of this research were (1) to test different approaches to characterize the relationship between weather and corn yields and (2) to develop yield models to simulate corn yields and optimal nitrogen rates for two soil groups using historic weather data.

Experimental yield data used in this study came from 77 simple fertilizer trials, which were carried out with unirrigated corn in farmers' fields, in the El Bajio area of central Mexico during the period of 1962-1965.

II. LITERATURE REVIEW

A. Water Deficit and Crop-Yield Relationships

To study the effect of water deficit on crop yields, researchers have used different methods. Among the approaches used are the following: (1) rainfall amount and rainfall distribution during the growing season, (2) drought criteria, (3) soil moisture as a step more closely related to crop production, and (4) plant-water status during the growing season.

1. Rainfall amount and distribution

In studying the relationship between rainfall and corn yields, both large geographical areas and/or experimental plots have been used. The statistical methods used to study this relationship have included simple correlation coefficients, simple and multiple regression techniques, and Fisher's regression integral and its adaptations. Seasonal, preseasonal, monthly, weekly, etc. rainfall data based on the calendar date have usually been used to establish this relationship (Wallace, 1920; Runge and Odell, 1958; Thompson, 1969, Isfan, 1979). However, few scientists have used phenological periods, i.e., different stages of development of the crop (Smith, 1914; Dale, 1948; Ortiz-Solorio, 1974).

The literature includes many reports on the effect of rainfall on crop yields. Sanderson (1954) reviewed many of the statistical crop yield-weather studies, and Dale (1948) reviewed the literature concerning the effect of rainfall on different phenological growing stages of corn. The research reported on here will be on those giving more importance to the methodology used rather than to the research results.

Hooker (1907) was probably the first scientist to apply correlation methods to the study of crop-weather relationships. His work served as a model for many subsequent investigations. Smith (1914) studied the effect of rainfall and temperature relative to the phenological periods on the corn yields. Using weather records and corn yields for Ohio, he found that July rainfall was the most significant variable. Smith concluded that the 10-day period after tasseling had the greatest effect on corn yields. The correlation coefficient for this particular phenological period was r = 0.74.

Wallace (1920) was one of the first to use multiple regression techniques to study the crop yield-weather relationships. In a study done in the U.S. Corn Belt, he reported that corn yields were highly correlated with weather factors in the southern half of the Corn Belt where low seasonal rainfall and high temperatures are experienced. However, in the core of the Corn Belt, where weather conditions are at or near optimum for the corn crop, he found lower correlations. This result was confirmed by Basile (1954) who found high correlations between precipitation and corn yields in the northwestern corner of the Corn Belt, where climatic conditions are not favorable for high corn yield. He pointed out that the work done in that region has shown general relationships of increased corn yields with increasing amounts of precipitation.

Pengra (1946), in a study done in South Dakota, reported that seasonal rainfall from April 1 to July 31 was higher correlated (r = 0.58) with corn yields than preseasonal precipitation (r = 0.36).

Another study between rainfall and corn yields using phenological periods was that conducted by Dale (1948). He studied the effect of rainfall in different phenological periods of the corn crop in five counties in Iowa. Using 26-year rainfall and corn yield data, this researcher computed simple correlation coefficients between different rainfall periods and corn yields. He used the date of 75% silking as a reference point for the crop calendar. He found that the simple summation of rainfall occurring in the period six weeks before and three weeks after silking accounted for the greatest effects of rainfall on corn yields. The correlation coefficients found by Dale in these five counties for the 9-week critical period ranged from r = 0.45 to r = 0.73, all being significant. Finally, he reported that rainfall for the 9-week critical period had a significant curvilinear effect on yield in only two of the five Iowa counties.

Pesek et al. (1967) developed weather indexes to include them as independent variables in a generalized production function. Daily rainfall during July and August was measured in 10-day periods, and deviations from an average amount, $\bar{R}$, were computed for each period. All negative deviations were added together. If there was no rainfall in any 10-day period, that deviation was given double weight. The sum of the negative deviations over the six 10-day periods was used to express the rainfall index R. It was assumed that no detrimental effects on yield would occur if any excess moisture was present during this two-month period.

Thompson (1969) used multiple linear regression equations to study the effect of weather variables and technology trend on corn yields in five Corn Belt states. Using this technique, he reported that technological trend and July rain explained most of the corn yield variability, although June, July, and August temperature and preseasonal temperature were also important. Highest corn yields were associated with about normal June temperature, below-normal July and August temperature, and above-average rainfall in July.

Recently, several researchers (Ortiz-Solorio, 1974; Volke-Haller, 1977; Isfan, 1979; Achutuni, 1978) have used total rainfall amounts during different periods (preseasonal, seasonal, monthly, weekly etc.) to study the relationship between rainfall and corn yields. Isfan (1979) studied the relationship between precipitation, N rate and corn yield to develop a criterion to forecast optimum N rates for corn during the spring. This study was carried out in Romania on a chernozem soil in a continental temperate climate characterized by an average annual precipitation of about 500 mm. Using 14 years of data, this investigator found that optimum N rate was more highly correlated with preseasonal precipitation (r = 0.77) than with summer precipitation (r = 0.41). He suggested that winter precipitation could be used to predict the optimum rate of N fertilizer.

Another approach to study the effect of rainfall on crop yields is the regression integral concept introduced by Fisher (1924). In developing this method, Fisher considered that, when studying the influence of rainfall on crop yields, not only the total amount of rainfall during the season should be considered but also its distribution during the season. This is because the effect of a given amount of rainfall can be different depending on when it occurred during the growing season. By using this technique which makes use of orthogonal polynomials, the growing season can be divided into as many periods as desired, each one independent of each other, and without increasing the number of independent variables.

This technique has been used by several researchers (Davis and Harrel, 1942; Dale, 1948; Carmen, 1963; Shah, 1965; Puente-Berumen, 1969) to characterize and estimate the influence of weather factors on crop yields.

Although this method presents an attractive conciseness, since it can represent the average effect of a weather variable on yield, it also has several limitations. Sanderson (1954) mentioned the limitations of this technique, pointing out its tendency toward excessive smoothing, failure to take into account joint effects between the weather variable in successive periods, and its unsuitability for the study of curvilinear relationships between weather and crop yields. Another disadvantage of this method, as pointed out by Dale (1948), is the distortion in the tails of fitted curves. He suggests that Fisher's regression integral might not be suitable when dealing with phenological-period rainfall.

In order to reduce some of the limitations of Fisher's regression integral, Hendricks and Scholl (1943) used an adaptation of the method to fit corn yield functions to temperature and precipitation data. Runge and Odell (1958), Runge (1968), and Leeper et al. (1974) used this modified Fisher's method to study the influence of rainfall and temperature during the growing season on corn yields.

As shown in the preceding paragraphs, the use of rainfall to assess the effect of water deficit on crop yields has been successful in some cases, whereas in others, this approach has failed. Shaw (1977) has pointed out that total seasonal rainfall in Iowa has generally not given a high correlation with yield. This is partly because of negative correlations for growing periods with excess moisture and positive correlations for growing periods that experience lack of moisture. As a result of that, both wet and dry periods cancel out each other, and the correlation between seasonal rainfall and yield is generally low.

Baier (1967) has pointed out several reasons that explain the poor relationship between weather factors and crop yields: the plant-weather relationship was too complex to be expressed by simple equations; statistical techniques were not the correct ones; mean meteorological values did not reflect the variations of environmental parameters over time; the meteorological elements selected were not appropriate measures of the physical environment and/or the interaction between meteorological elements was not considered.

On the other hand, Watson (1963) and Sanderson (1954) stated that, in regions where only one weather element is limiting crop production, correlation and regression methods have generally been successful in estimating the effect of weather on crop yields.

Thus, it can be concluded that the degree of success in using direct climatic elements to explain yield variation is, in general, a function of the specific conditions under which the research is conducted.

2. Drought criteria

The methods of defining agricultural drought have generally been based on either precipitation thresholds during a given period of time, or arbitrary available soil moisture capacities. Palmer (1965), in his publication "Meteorological Drought", discussed the different definitions given to drought.

One of the first studies on agricultural drought was reported by Blumenstock (1942) who presented an analysis of runs of dry days. He assumed that a run of dry days ended just prior to any 48-hour period during which 2.54 mm or more of rainfall was received. In crop production, this definition of drought has little significance since the occurrence of such an amount of rainfall might not change the condition of soil moisture in the rooting zone of a crop.

Barger and Thom (1949) defined agricultural drought as a condition of rainfall deficiency with respect to crop production. They conducted a study in Iowa to characterize drought intensity in corn using county corn yields and rainfall records. The criterion of drought, as developed by these researchers, was based on the association of certain minimum required total rainfall amounts within time intervals of different duration, i.e., the amount of rainfall which will just permit normal corn development during a period of n consecutive weeks is the minimum required total rainfall for that duration. The maximum rainfall deficiency with respect to these base amounts recorded for any period of weeks during a corn-growing season constitutes a measure of the drought effect on the final yield of the crop. They correlated the maximum rainfall deficits and deviations of county corn yields from normal and found that, for years in which drought conditions occurred, from 25 to 60% of corn yield variability was explained by this criterion.

Myers and Shaw (1959) presented probabilities of runs of dry days at Ames and Corydon, Iowa. They defined a dry day as one with less than 5.08 mm rainfall.

van Bavel (1953) attempted to define agricultural drought not only in terms of rainfall data but also by using plant and soils factors. He introduced a method which included the amount and distribution of rainfall, evapotranspiration, and plant-available water capacity to the rooting depth. He defined agricultural drought as a condition in which there is insufficient soil moisture available to a crop. He also defined a drought-day as one in which potential evapotranspiration exceeds an arbitrary available soil-moisture capacity previously established.

Agricultural drought, as defined by van Bavel, accounts for only the duration of moisture deficiency. It should be noted, however, that the magnitude of such a moisture deficiency is another factor to be considered in assessing the severity of drought on crops.

The concept of drought-days developed by van Bavel (1953) was used by Parks and Knetsch (1959) who studied the interaction of drought-days and nitrogen fertilizer using experimental corn yield plots. They defined drought-days as those in which a water balance showed no available soil moisture. They reported that a combination of linear and quadratic terms for level of nitrogen, a linear weighted drought-day term, and the drought-day x nitrogen interaction explained 97% of the yield variation between corn yields from 5 replicated treatments in 3 years.

In Mexico, Laird and Rodriguez (1965) applied the van Bavel method to compute drought-days using part of the same experimental plot corn yields used in this thesis.

Ewalt et al. (1961) studied the effect of drought on corn yields in Missouri. Drought intensity was estimated by rainfall and by two water balance methods based on Penman's and Thornthwaite's methods. Drought days were considered as those with no available soil moisture. Regression equations expressing corn yields as a function of seasonal, monthly, and weekly drought-days, as well as weekly rainfall, were computed. They found that weekly rainfall explained more ($R^2 = 0.75$) corn yield variation than the number of drought-days ($R^2 = -0.68$) as determined by Penman's method. Their analysis suggested that rainfall during the last week in June and during the early weeks of July had the greatest effect on corn yield in Missouri.

Sopher et al. (1973), working with well-drained and poorly-drained soils in North Carolina, developed a drought index to study the effect of drought-days on corn yields.

They defined a drought-day as a 24-hour period when potential evapotranspiration (as determined by Thornthwaite's (1948) method) exceeds rainfall plus the available soil-moisture capacity. This drought index was weighted according to physiological growth periods. They reported that drought-days accounted for 62.6% of the corn yield variation on the better-drained soils. However, on the poorly-drained soils, drought-days explained only 41.2% of the yield variation. This was attributed to moisture extraction from an underlying water table. They concluded that, on these poorly drained soils, excess moisture and cool temperatures should be included, along with drought measures early in the growing season.

In attempting to avoid many of the complicating biological factors and arbitrary definitions about agricultural drought, Palmer (1965) proposed another approach in which drought severity is dependent on the duration and magnitude of the abnormal moisture deficiency. He developed a normalized meteorological drought index, which permits time and space comparisons of drought severity for individual areas relative to departures from normal for each area.

3. Evapotranspiration and moisture stress

In this section, the concepts of potential evapotranspiration, actual evapotranspiration, and moisture stress and its effects on crop yields will be reviewed.

a. Potential evapotranspiration Penman (1956) defined potential evapotranspiration (PET) as "the amount of water transpired in unit time by a short green crop, completely shading the ground, of uniform height, and never short of water." According to this definition, PET from well-watered crops completely covering the soil depends primarily on the weather, with plant and soil factors being of secondary importance (Hillel, 1980). PET, seen as the atmospheric demand for water, is a function of solar radiation, wind, humidity, and temperature, with solar radiation being the most important weather factor (Shaw, 1977).

There are various techniques by which evapotranspiration (ET) can be measured. Tanner (1967) divided measurements of ET into three types: (1) water balance or hydrologic methods, (2) micrometeorological methods, and (3) empirical methods. Water balance methods, including lysimeters and micrometeorological methods, are designed to measure actual evapotranspiration, whereas empirical methods estimate PET, since those methods are based on standard climatic measurements only. Estimates of PET made by empirical methods must be calibrated using plant and soil factors to relate it to actual ET, as pointed out by Tanner (1967).

Although micrometeorological methods have a rational basis, their use in measuring ET is limited, due mainly to necessary data rarely being available. These methods, as well as lysimeters, are used in basic micrometerological studies, and their use in large geographic areas is restricted due to the high cost.

On the other hand, empirical methods are based on standard meteorological measurements only, which generally are available; these methods can be used over large areas where estimates of PET are required.

Some of the more important empirical methods have been developed by Penman (1948), Thornthwaite (1948), and Blaney and Criddle (1950). These and other empirical methods were reviewed by Jensen (1973) who presented and compared several estimation techniques from the perspective of accuracy and necessary inputs. He concluded that no single existing method is universally adequate under all climatic conditions and that the method selected will depend on available meteorological data, training and experience of the user as well as accuracy required in the estimates.

Empirical methods are based on one or more weather elements. The estimation technique created by Thornthwaite uses temperature as the only weather input, whereas the method developed by Penman requires inputs of net radiation, sunshine, relative humidity, temperature and wind speed. Evaporimeters measure the drying ability of the air, which is a function of solar radiation, wind, temperature and the vapor pressure deficit (Fritschen and Shaw, 1961). Since evaporation from evaporimeters is governed by micrometeorological conditions, it would be expected to show a high correlation with PET. Tanner (1967) stated that evaporimeters are highly correlated with PET over appropriate time periods (such as weekly or monthly periods), even though the pans and atmometers are poor analogues of a vegetation surface. Shaw (1982) believes that pan evaporimeters can be good estimators of PET and can be converted to crop evapotranspiration under certain conditions, such as large geographic areas, where extreme accuracy is not required. However, the use of evaporation pan data may be of limited use in dry climates, where a large advection of sensible heat takes place (Rosenberg, 1974).

b. Actual evapotranspiration (AET) Actual evapotranspiration is generally lower than PET. This is because AET is affected by the extent of ground cover, the crop growth stage, the available soil moisture, as well as by climatic factors.

The extent of ground cover and the crop growth stage affect evapotranspiration either by affecting the energy intercepted by the crop canopy or by the root system affecting the availability of water. In row crops, like corn, which present a changing crop surface, adjustments accounting for the crop cover are very important, as pointed out by Shaw (1982). During the early growth stage where there is a partial crop cover, water use is lower than that with a full crop cover (Shaw and Burrows, 1966). This is because soil moisture loss occurs primarily by evaporation from the surface of exposed soils which is frequently low in soil moisture, resulting in a lower rate of loss. As the crop grows, the leaf area increases and the amount of water loss by transpiration increases, whereas that lost by evaporation decreases. Toward the end of the growing season, as corn plants approach maturity, their physiological activity declines and transpiration decreases.

Denmead and Shaw (1959) presented a curve that shows the change of the ratio of evapotranspiration of corn to class A open pan evaporation throughout the growing season, under no moisture limitation for transpiration. Surface evaporation may not have been at the potential rates. They observed that the ratio increased in a sigmoid manner from a value of 0.36 at planting to 0.81 at silking. This value of 0.81 remained constant for 16 days after silking and then declined. It can be concluded from these data that only during the 16-day period following silking could actual evapotranspiration equal potential evapotranspiration.

As mentioned before, actual ET is also affected by the depth of water extraction by the roots, because this affects the availability of soil moisture. Rooting depth is affected by soil moisture content, mechanical impedance, and soil fertility level, among other factors. Bowen (1981) discussed the factors involved in mechanical impedance. He stated that mechanical impedance is caused by excessive soil compaction and this reduces the quantities of water and nutrients available to the plant.

With an adequate level of soil moisture, the depth of extraction is not important, since the bulk of moisture removal comes from the shallower depths where most of the rooting system is located. However, as the water supply is reduced, large differences in rooting pattern may occur. In addition, soils with clay pan subsoils may not have roots as deep as a good permeable soil. Russell and Danielson (1956) reported on the time and depth patterns of water use by corn. They found that on deep, permeable, well-drained soil the corn was able to use water to a depth of five feet or more. Holt and Van Doren (1961) concluded that soil-moisture supply and rate of water usage determine the depth to which corn plants extract water.

Shaw (1963) presented a water extraction pattern from the soil profile at different depths during the growing season for corn. He has used this extraction pattern to predict soil moisture in Iowa and he has stated that under wet conditions the extraction pattern is only to 4 feet; whereas under normal and dry conditions the extraction pattern is up to 5 and 7 feet, respectively.

As mentioned earlier, actual evapotranspiration is dependent on the soil-moisture supply. As available soil moisture decreases, it is expected that evapotranspiration decreases below its potential value. This has been observed by various researchers (Slatyer, 1956; Makkink and Heemst, 1956; Denmead and Shaw, 1962).

To determine the availability of soil moisture for plants, the concepts of field capacity and the permanent wilting point must be known. Hillel (1980) has criticized these soil-water constants, pointing out that field capacity and permanent wilting point are static concepts, and that soil-water availability to plants should be considered as part of a dynamic system which involves properties of the soil, properties of the plant, and also meteorological conditions. Despite its limitations, Slatyer (1967) and Kramer (1969) concluded that, for many practical purposes, they can be used in this way. The upper limit of water availability to plants (field capacity) is the water left in the soil after excess gravitational water has drained from the soil profile, and the wilting point is the lower limit to which plants can extract soil moisture when under very low moisture demand (Shaw and Burrows, 1966). The range of available water is the difference in water content between field capacity and the permanent wilting point.

Several concepts regarding the availability of soil water to plants have been proposed over the years (Halstead, 1954; Pierce, 1958; Thornthwaite and Mather, 1955; Veihmeyer and Hendrickson, 1955). These range from equal availability from field capacity to wilting point (Veihmeyer and Hendrickson, 1955) to a linear relationship where availability decreases gradually as the soil-moisture content decreases (Thornthwaite and Mather, 1955). Although the individual relationships proposed seem to differ, they all fit under the theoretical work of Philip (1957) and Gardner (1960) who have shown that soil-moisture availability is the result of the amount of moisture in the soil, the texture of the soil, the water status in the plant, and the atmospheric demand for water.

The relationship between soil-moisture content and transpiration rates for different types of demand days for corn plants grown in containers in the field was studied by Denmead and Shaw (1962). They found that on a clear, dry day with high atmospheric demand only corn plants with a high soil-moisture content met the potential transpiration rate. However, on an overcast, humid day potential transpiration was met by moisture supplies very near the wilting point. Thus, if soil-moisture content is lower than the minimum required to meet the atmospheric demand for that particular day, actual transpiration will be below its potential and plants will be under some degree of moisture stress.

Based on the daily balance between soil moisture and atmospheric demand, Dale and Shaw (1965), Corsi and Shaw (1971) and Shaw and Felch (1972) developed different indexes to evaluate moisture stress in Iowa. The basis for these indexes is the reduction in actual evapotranspiration from potential evapotranspiration. Dale and Shaw (1965) considered a stress day when the evapotranspiration was reduced below its potential rate.

c. Effect of moisture stress on crop yields Moisture stress can affect various morphological and physiological processes in the plant. The most important are leaf enlargement, stomatal behavior, photosynthesis, respiration, translocation, and distribution of assimilates (Begg and Turner, 1976) which eventually will affect crop yields. Salter and Goode (1967) have summarized the effects of moisture stress at different stages of development on crop growth and yield for different crops. Downey (1971) reviewed much of the research dealing with the effect of moisture stress on corn. He showed that relative net photosynthesis is reduced if relative turgidity in the leaves is below 90%, and it may be practically zero if relative turgidity drops to the 70% level.

The effect of soil-moisture stress at different stages of growth of corn and its influence on yield has been a subject of study by a number of researchers (Miller and Duley, 1925; Robins and Domingo, 1953; Denmead and Shaw, 1960; Wilson, 1968; Claassen and Shaw, 1970; Mallet, 1972). Shaw (1977) recently reviewed the topic and concluded that the greatest yield reductions due to moisture stress result when the stress occurs near the period of tasseling, silking, and pollination. He noted also that the degree of stress in corn plants can be reduced if a high level of fertility is maintained. However, this is difficult to maintain, especially when corn is under rainfed conditions. The top layer of soil may be dry and moisture and nutrient stress may develop under these circumstances.

Stress indexes have been used to study the relationship between corn yields and moisture stress. Morris (1972) pointed out that the use of stress indexes to estimate yields can be more accurate than using raw meteorological elements, because these indexes represent an integration of several meteorological factors which represent a more direct influence of climate on crops and because possible intercorrelation among weather elements is eliminated. Dale and Shaw (1965) studied the combined effects of weather and stand on corn yields under two fertility levels. They found a high correlation between stress index and experimental plot corn yields. The stress index comprised a 9-week period, from 6 weeks before silking to 3 weeks after silking. A regression equation including this stress index along with stand and technological trend was associated with 83% of the corn yield variation over the 1933-1962 period.

Shaw (1974) developed a weighted stress index for corn in Iowa to study the relationship between moisture stress and corn yields. His weighted index comprised an 85-day period, 40 days before silking and 45 days after silking. He found correlation coefficients of -0.88 and -0.83 between actual yields and high and moderate yielding sites, respectively, for the two regression equations computed to estimate corn yields.

In Iowa, a number of researchers have used a moisture-stress index, as described originally by Dale and Shaw (1965), to characterize the weather factor. This stress index, along with soil and management variables, has often been used in studying the effect of these factors on crop yields (Voss and Pesek, 1967; Desselle, 1967; Voss et al., 1970; Morris, 1972; Henao, 1976; Pena-Olvera, 1979; Sridodo, 1981).

4. Plant-water status

The status of water in the plant represents an integration of the atmospheric demand, soil-water potential, rooting density and distribution, as well as other plant characteristics (Kramer, 1969). Ideally, it would be desirable to have a measurement of the plant-water status in explaining the relationship between crop-water deficits and crop yields. The response of crops to water stress has been reviewed by many researchers. Some important references are given as follows: Hsiao (1973, Slatyer (1967), Begg and Turner (1976), Mussell and Staples (1979), Turner and Kramer (1980), and Levitt (1980).

The effects of water stress on crops can be described in terms of the plant-water content or the energy status of the contained water, usually expressed as total water potential (Barrs, 1968). In discussing the effect of water deficits on crops, the term of total water potential will be used.

It is generally accepted that water moves through the soil-plant-atmosphere continuum along a gradient of decreasing water potential from the soil, through the plant to the atmosphere (Slatyer, 1967). This lowered water potential in the transpiration pathway provides the driving force for the movement of water out of the plant. As a result of this loss, water deficits develop in the leaf, stem, and root tissues (Begg and Turner, 1976).

Since the plant can only extract water from the soil when its water potential is lower than that in the soil, the water in the plant is seldom in equilibrium with the water in the soil (Begg and Turner, 1976). The soil and plant water potentials change as the soil dries out. These progressive changes are presented schematically in Figure 1 (Slatyer, 1967). This assumes the same evaporation conditions occur each day. The top curve shows how the water potential in the soil, ψ soil, changes from an initially wet soil (ψ soil $\simeq 0$) to a condition of low soil moisture (ψ soil = -15 bars). The other curves

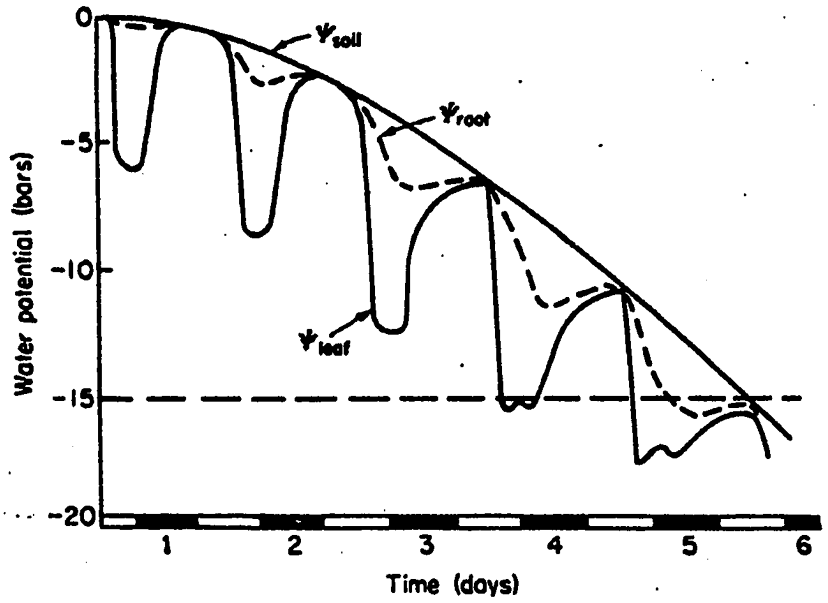

Figure 1. Schematic representation of changes in leaf water potential (ψ leaf), root surface water potential (ψ root) and soil water potential (ψ soil) as transpiration proceeds from a plant rooted in initially wet soil (ψ soil = 0); the same evaporative conditions are assumed to prevail each day; the horizontal dashed line indicates the value of ψ leaf at which wilting occurs (from Slatyer, 1967)

show the water potential at the root surface, ψ root, and in the leaves, ψ leaf, assuming 12 hours of day and 12 hours of night. It is interesting to note, however, that under variable atmospheric demands, the pattern of ψ leaf may be different from that presented in Figure 1 (Shaw, 1982).

The total water potential ψ is a sum of component forces acting on the water in a system. Begg and Turner (1976) have defined water potential ψ in plants as follows:

$$\psi = \pi + P + \tau + G + I \quad ,$$

where:

π is the osmotic potential due to the presence of solutes in plant cells,

P represents the pressure potential (also called turgor pressure),

τ represents the matric potential component,

G is the gravitational potential due to gravitational forces, and

I is an interaction term, since the components of water potential are not completely additive.

The gravitational potential and the interaction term between π and τ are small and are considered of little influence in the total water potential for most crops (Begg and Turner, 1976); then, water potential can be expressed by the equation:

$$\psi = \pi + P + \tau \quad .$$

Begg and Turner (1976) have observed that τ approaches zero for fully turgid tissues. Under such conditions, ψ could be expressed as a function of osmotic and pressure potential, Hsiao et al. (1976) have supported this, concluding that such a relation is valid for tissues ranging from fully turgid (100% relative water content) to about 40% relative water content (tissues badly dehydrated). Therefore, leaf water potential can be expressed by the equation, $\psi = \pi + P$, which is the expression normally used to study water stress in crops. When plants are under water stress, P which normally is positive approaches zero and π, a negative term, becomes more negative; consequently, the total water potential ψ is lowered.

According to Barrs (1968), plant water status can be measured using direct or indirect methods. Direct methods include relative water content, sometimes called relative turgidity, and total water potential and its components which are among the most used (Barrs, 1968).

There are a number of indirect methods available for the measurement of water deficits. These include visual symptoms of stress such as wilting, or color changes of foliage, leaf thickness, changes in stem diameter, fruit diameter or stomatal aperture, and measurement of leaf temperature by infrared thermometry (Begg and Turner, 1976). Idso et al. (1977, 1978, 1980) have used plant temperature to characterize plant stress.

In addition, based on leaf-air temperature differentials, they developed a crop-water stress index, which, with the use of remote sensing techniques, has been found useful for scheduling irrigations and predicting crop yields.

Laird (1968) and Turrent-Fernandez et al. (1973) developed a method to characterize water stress in the corn crop. This method, based on visual symptoms of wilting, consists of two components: the frequency of plants showing signs of wilting and the intensity of the wilting. The frequency component is noted by recording the number of plants per plot, or the percentage of plants, with a given intensity of wilting. The intensity component includes three levels, namely, no wilting, moderate wilting and severe wilting, to which are assigned weights of 0, 0.5 and 1.0, respectively. The degree of stress for a particular day is computed using the following equation:

$$WPI = \frac{n_1 \times 0 + n_2 \times 0.5 + n_3 \times 1.0}{n_1 + n_2 + n_3} ,$$

where:

WPI = wilting plant index,

n_1 = number or percent of plants with no wilting,

n_2 = number or percent of plants with moderate wilting,

and n_3 = number or percent of plants with severe wilting.

The equation above indicates that WPI may range from zero (no wilting) to 1.0 (severe wilting). The sum of these daily wilting-plant indexes over the growing season of corn gives what Laird et al. (1969) have called a drought index. This approach to characterize plant water stress and its effect on crop yields has been used by several researchers (Puente-Berumen, 1969; Villalpando-Ibarra, 1975; Ruiz-Vega, 1979; Volke-Haller, 1977).

Ruiz-Vega (1979), working in the state of Oaxaca, Mexico, computed correlations between corn yields and a drought index developed in a slightly different way but using the same principles previously described. He found a correlation coefficient of -0.90 between this drought index and yield for plain deep soils, while in the shallow sloping soils, r = -0.83 was obtained.

B. Effects of Excess Moisture on Crops

1. General overview

It is estimated that approximately 12% of the soils in the world have excess moisture (Dudal, 1976). The damage caused to crops by excess moisture is difficult to evaluate because many factors interact simultaneously. It is recognized that the extent of damage caused by flooding of standing crops is dependent on soil type, plant species, growth stages, day-length, temperature at the time of flooding (injury to crops is more severe when they are flooded on hot days), and duration of the flooding (Cannell and Jackson, 1981; Russell, 1959). The subject of plant response to excess soil moisture has been reviewed by a number of researchers. The most recent reviews are those by Morris (1972), Russell (1977), Levitt (1980), and Cannell and Jackson (1981). The reader can find additional information in those reviews.

Excess moisture restricts the supply of oxygen to roots and soil organisms in two ways: first, by displacing air from the soil and, second, by slowing oxygen diffusion (Cannell and Jackson, 1981). In the first case, air-filled pores are replaced by water-saturated pores and, in the second case, the decrease of oxygen diffusion is due to oxygen diffusing in water about 10^4 times more slowly than in air. The presence of water-filled pores caused by excess moisture is the main restriction to soil aeration.

The critical level of air porosity at which detrimental effects due to excess moisture may occur has been investigated by a number of researchers. Kohnke (1968) stated that normal growth of most crop plants is possible only if the concentration of soil oxygen is greater than 10%, and crop growth is restricted when the oxygen content of the soil air sinks below 10%. Grable (1971) and Greenwood (1971) have also suggested an empirical estimate of 10% air-filled space to avoid anaerobic conditions; however, they recognized that this estimate depends on the distribution and continuity of pores and the demand for oxygen.

Many exceptions to this rule of 10% exist. Bateman, 1963 (cited by Grable, 1966), noted that a change in porosity of Drummer silty clay loam from 22 to 11% by compaction significantly reduced corn yields, but similar changes in Thorp silt loam had no effect on yields. Another reason for variation in upper and lower critical levels of air porosity for plant growth is that crop species vary greatly in their ability to grow in soils with low air porosity. Vomocil and Flocker (1961) showed that on soils where air-filled porosity levels ranged from 5 to 15% of the soil volume, there was a significant decrease in growth and yield for various crops. Kohnke (1968) reported that tomatoes, potatoes and sugar beets are high soil-oxygen demanding crops; while corn, soybean and wheat are considered as intermediate; and most grasses grow well even at restricted soil-aeration levels. Therefore, the evidence presented here shows that no single value of air porosity can be considered optimum, or even minimum, for all situations.

The fact that the minimal level of air porosity for optimum crop growth varies with crop type, soil type and several other factors mentioned at the beginning of this section demonstrates that a single value of air porosity is not always critical from the standpoint of aeration. Cannell and Jackson (1981) in their review presented several types of avoidance processes by which crops can reduce the injury from waterlogging. They mentioned the production of adventitious roots which grow in the well-aerated soil surface, the development of channels (aerenchyma) that may permit the internal aeration of submerged parts, and shoot responses that minimize damage from excess moisture (slowing of growth, senescence and abscission of the older leaves, rapid closing of stomata etc.) among other mechanisms of avoidance.

Levitt (1980) discussed the adverse effects of waterlogging soils on plant growth. He concluded that although excess moisture due to flooding cannot produce a primary water-potential stress because it involves no change in the free energy of the water, it can affect the plant by way of secondary flood-induced stresses. Excess moisture in soils can cause the following adverse effects: (1) reduced root respiration, (2) restricted water and nutrient uptake and interference with the formation and translocation of plant hormones, (3) increase of CO_2 and ethylene which may lead to accumulation of toxic substances as well as suppression of key enzymatic activities, (4) leaching of mineral nutrients, and (5) alteration in chemical characteristics of the soil favoring denitrification and reduction of ions to more soluble and toxic forms to plants.

2. <u>Corn yield reductions due to excess moisture</u>

Excess moisture in corn generally causes greatest yield reductions early in the growing season, while the root system is small and near the surface. Johnson (1953) found that flooding corn plants for a period of 6 or 10 days in the early vegetative or vegetative stages was more harmful than heavy irrigations applied in the early reproductive and pretassel stages. Excess-moisture treatments were associated with grain-yield reduction, delay in silking and pollen shedding, high kernel moisture at harvest time, and reduction in length of roots and height of corn plants. In another study, Joshi and Dastane (1966) found that flooding at the preflowering stages reduced corn yield 31%, as compared to the unflooded control.

Ritter and Beer (1969) reported from a field study in Iowa that flooding when corn was 15 cm in height for 72, 48 and 24 hours reduced corn yields by 32, 22 and 18%, respectively, at low N fertilizer level. At a high nitrogen level, these reductions ranged from 19 to 14% in one year to less than 5% the next year. However, at silking, heavy irrigations increased corn yields when ample nitrogen was present, and yield reductions up to 16% occurred with 96 hours of flooding at the low level of nitrogen. From the significant interaction between time of flooding and nitrogen level, these researchers concluded that there was a significantly larger difference in yield between the high and low nitrogen plots for the first flooding period (plants at 15 cm of height) than for the third flooding period (plants at silking).

Significant corn-yield reductions caused by excess moisture have also been reported by Chaudhary et al. (1975) and Lal and Taylor (1969). DeBoer and Ritter (1970), in a field experiment carried out in depression areas of north-central Iowa, found that corn 30-cm high was killed by 3-4 days of flooding and by 6 to 7 days of flooding when plants were 50 to 60 cm high. However, Ali (1976) found that flooding for 1 to 4 days at the 7 to 10 leaf stage (6 weeks after planting) had greater effects than at the 4 to 5 or 14 to 15 leaf stage.

3. Modeling the effect of excess moisture

In recent years, there have been several attempts to estimate the effect of excess moisture on crops through the use of simulation models based on empirical functions previously developed (Morris, 1972; Makkink and van Heemst, 1975; Skaggs, 1978; Stuff and Dale, 1978; Loveland, 1980).

Morris (1972) developed a simulation program to estimate excess-moisture indexes using soil and climate data collected at many farmers' fields during the period of 1957 to 1970 in several Iowa counties. He used these indexes as independent variables in regression equations to explain corn-yield variation. The best excess-moisture index from those developed by this researcher included the number of days during a 46-day period beginning 3 days after the planting date in which the air space in the root zone was estimated below 10% by volume. In addition, this index was weighted, giving more weight to the earlier growing stages and assuming a linear decrease in detrimental effects caused by excess moisture as the crop approaches the reproductive stage. This index significantly explained corn-yield variations, both alone and in combination with other independent variables.

In another simulation study, Loveland (1980) modified the soil-moisture program as originally developed by Shaw (1963), to account for the effect of excess moisture on corn yields in a reclaimed mine soil in Iowa. He represented the period of excess moisture in the modified model by an index of excess moisture. This index included the number of days during which air porosity of the top foot was less than 10% of the total soil volume, for a 54-day period beginning from planting date. The excess moisture, along with a moisture-stress index, was computed for the years of 1978 and 1979, which were used to calibrate the modified version and to test its accuracy. This excess-moisture index caused a yield reduction in approximately 27% of the years in the 22-year period he used in making this corn-yield simulation.

C. Crop-Yield Predicting Models, Development and Evaluation

1. Types of models

Since a considerable portion of the present research is about modeling the effect of climate on plot corn yields grown under variable soil and management levels, it was considered important to include a brief review about the different procedures available for development and evaluation of crop-weather models.

Baier (1979), in a review of crop-weather models' terminology, classified these models as follows: (1) crop-growth simulation models which are defined as a mathematical representation of the complex physical, chemical and physiological mechanisms underlying plant processes, where the effect of meteorological variables on specific processes such as photosynthesis, transpiration or respiration can be simulated by means of a set of mathematical equations which are based on experimental or available knowledge of the particular process; (2) crop-weather analysis models which provide a running account of the daily accumulated crop response to selected agrometeorological variables as a function of crop development; and (3) empirical-statistical models which use a sample of yield from an area (experimental plot, crop district or region) and a sample of weather and soil data from the same area to produce estimates of coefficients by some sort of regression technique.

Baier (1978) has pointed out that the validity and potential application of empirical-statistical models depend on the representativeness of the input data, the selection of variables, and the design of the model. In addition, these types of models do not easily lead to an explanation of the cause and effect relationship. However, he concluded that it is a feasible procedure to use in assessing the effect of climate and soil variables on crop yields.

According to Baier's (1978) remarks, if we assume that input data are representative of the area of study, the problem in developing a good statistical model to be used in crop-yield prediction will depend upon the criterion used for variable selection. Draper and Smith (1981), in their book Applied Regression Analysis, extensively discussed the statistical procedures available to select variables. They concluded that these procedures do not necessarily lead to the same solution when applied to the same set of independent variables, although in many cases they will achieve the same answer. The best technique to use in a particular case will depend on the type of data. They also pointed out that all selection techniques are useful tools; however, none of them can compensate for common sense and experience.

2. Building procedures of regression models

Building a regression model for crop-yield prediction basically includes two stages: (1) development of the model, which consists in selecting those factors influencing crop yields, by using some of the criteria presented by Draper and Smith (1981) along with the experience of the researcher on the subject and (2) model evaluation, which includes checking the stability of the regression coefficients and checking the reliability of the crop-yield prediction model with data independent from those used in developing the model (Draper and Smith, 1981; Wilson and Sebaugh, 1981; Nelson and Dale, 1978).

To check if parameters are stable over a sample space and to check their accuracy in yield predictions by a model, Draper and Smith (1981) recommended the use of an independent data set to perform the test. They defined two types of data sets: (1) longitudinal and (2) cross-sectional. The first type is that used when the model has been built using observations taken across a long time span. In this case, the stability of the regression coefficients and accuracy in yield predictions can be tested using successive time periods from the longitudinal set of data. The second type, cross-sectional data sets, are those where information has been collected in space about the same time. In this case, they recommended leaving out part of the data and using this to evaluate the model. Stone (1974) discussed some procedures used to determine optimum subset splitting in model evaluation. Snee (1977) proposed another method which uses half of the data to develop the model and the other half to evaluate it. However, he recommends not to split data in half unless n (total sample size) > 2p + 25, where p = number of parameters in the predicting model.

In Brazil, Chen and da Fonseca (1980) tested the stability of the regression coefficients and the accuracy in yield predictions for a corn-yield predicting model. Based on the data period 1957-1975, these researchers found relatively stable regression coefficients and the predicting errors ranged from 1.97 to 4.32%, when extrapolating to independent test years after 1975. They concluded, however, that for an operational yield prediction, all the available historic data should be included in computing the regression coefficients of the multiple regression model.

The coefficient of determination (R^2) is another test which is generally used as a criterion for judging the worth of a prediction equation. However, in some instances, a high R^2 value does not necessarily mean that a regression equation is good for crop-yield prediction. The real value of any prediction equation can be determined only by applying it to independent data. Laird and Cady (1969) used three regression selection techniques, stepwise, backward elimination, and an approach based on agronomic considerations, to develop a yield-prediction equation for the same data used in this thesis. They found that the respective R^2 values for these models were largest for the full model, followed in descending order by backward elimination, stepwise and, finally, agronomic. But applying these models to data not used in estimating the coefficients for the regression equation resulted in relative efficiencies of the four models to be completely opposite. That is, the predictive mean squares for the agronomic model were least and the full model highest. One reason why the full and backward elimination models predicted poorly, as given by Laird and Cady (1969), was that these models included highly correlated variables whose coefficients are adequate for the particular set of observations used in their computation but inadequate for predicting when independent data are used. Based on these results, they suggested introducing into a regression model only variables whose observed values adequately cover the region of interest.

Nelson and Dale (1978) proposed a methodology for testing the accuracy of yield-prediction models, in which they use the absolute yield differences between model predictions and statistical reporting service (SRS) estimates, $|\hat{Y}_{Model} - \bar{Y}_{SRS}|$, for testing regression models. They used this methodology to test four statistical regression models for corn predictions of Indiana county corn yields. They found little difference among three of the four models. The average errors in corn yield predictions with the best three models were approximately 630 kg/ha (10 bu/acre).

Crop-yield prediction models are not only evaluated in relation to their reliability in yield predictions but also using other criteria that not necessarily are statistical tools. Wilson and Sebaugh (1981), working in the Agriculture and Resource Inventory Surveys through the Aerospace Remote Sensing (AgRISTARS) program, established the following evaluation criteria for crop-yield-prediction models: yield indication reliability, objectivity, consistency with scientific knowledge, adequacy, timeliness, minimum cost, simplicity and provision of accurate content of modeled yield reliability. Here, only the first and last of the criteria make use of statistical techniques for their evaluation.

3. Simulation models

Simulation of crop yields for long periods of time through the use of crop-yield-prediction models is one of the several areas of application of these models (Cady and Fuller, 1970). This is especially important in agricultural research where, because of cost and time, it is not possible to carry out field experimentation during many years. However, it may be feasible to develop and calibrate a yield-predicting model making use of research results, along with soil and climate data. Through the use of simulation models with the aid of a computer, it is easy to simulate the impact of climate variability for long periods on the yield response to different agronomic practices. Tillage practices, fertilizer amounts, and crop varieties, to mention just a few of the factors affecting yield, can be evaluated.

Kissel et al. (1975) developed a model to describe the yield of grain sorghum as a function of applied N and the degree of water deficit under field conditions in order to obtain more precise N fertilizer recommendation in the Texas

Blackland Prairie. They used six years (1963-1968) of experimental data to develop the regression model and four independent years (1971-1974) of data to test the model. These researchers found good agreement between measured and predicted grain sorghum yields. Based on these results, they used 60 years of climatic data to simulate the approximate number of stress days for each of the 60 years. These stress days and the nitrogen variable were included in an equation, which allowed them to estimate the impact of these two factors on sorghum yields for the 60-year period of climatic records used in this simulation. Finally, they used probability distributions of stress days for different initial levels of available soil moisture to recommend N fertilizer application rates to dryland grain sorghum. They concluded that through simulation models it is possible to make a more efficient use of fertilizer than the usual practice of basing N recommendations on the average response curve from several years of data.

III. DATA AND PROCEDURES

A. Area of Study

The area selected for this study is an important agricultural region of central Mexico, where unirrigated corn is the most important crop. This area is located in the western part of El Bajio and includes parts of the states of Guanajuato, Michoacan and Jalisco. It is situated geographically between meridians 101°15' and 103°30' west longitude, and between latitudes 20°15' and 21°10' north, at elevations varying from 1550 to 1870 m above sea level. Figure 2 shows the approximate location for the area of study.

1. Climate

The average annual rainfall varies from about 600 mm in the Silao area to nearly 950 mm in the southernmost part. The average temperature for the June-October period is around 22°C. According to Köppen's classification cited by Trewartha (1968), the climate of this region is a Cw type, which is characterized for having dry and wet seasons. The wet season comprises the period from June to October, when about 90% of the annual precipitation occurs, and during which the corn crop is grown. Figure 3 shows the average potential evapotranspiration (PET) as estimated by Thornthwaite's method (Thornthwaite and Mather, 1957) vs the average precipitation, using 10 weather stations, in the area of study. For eight

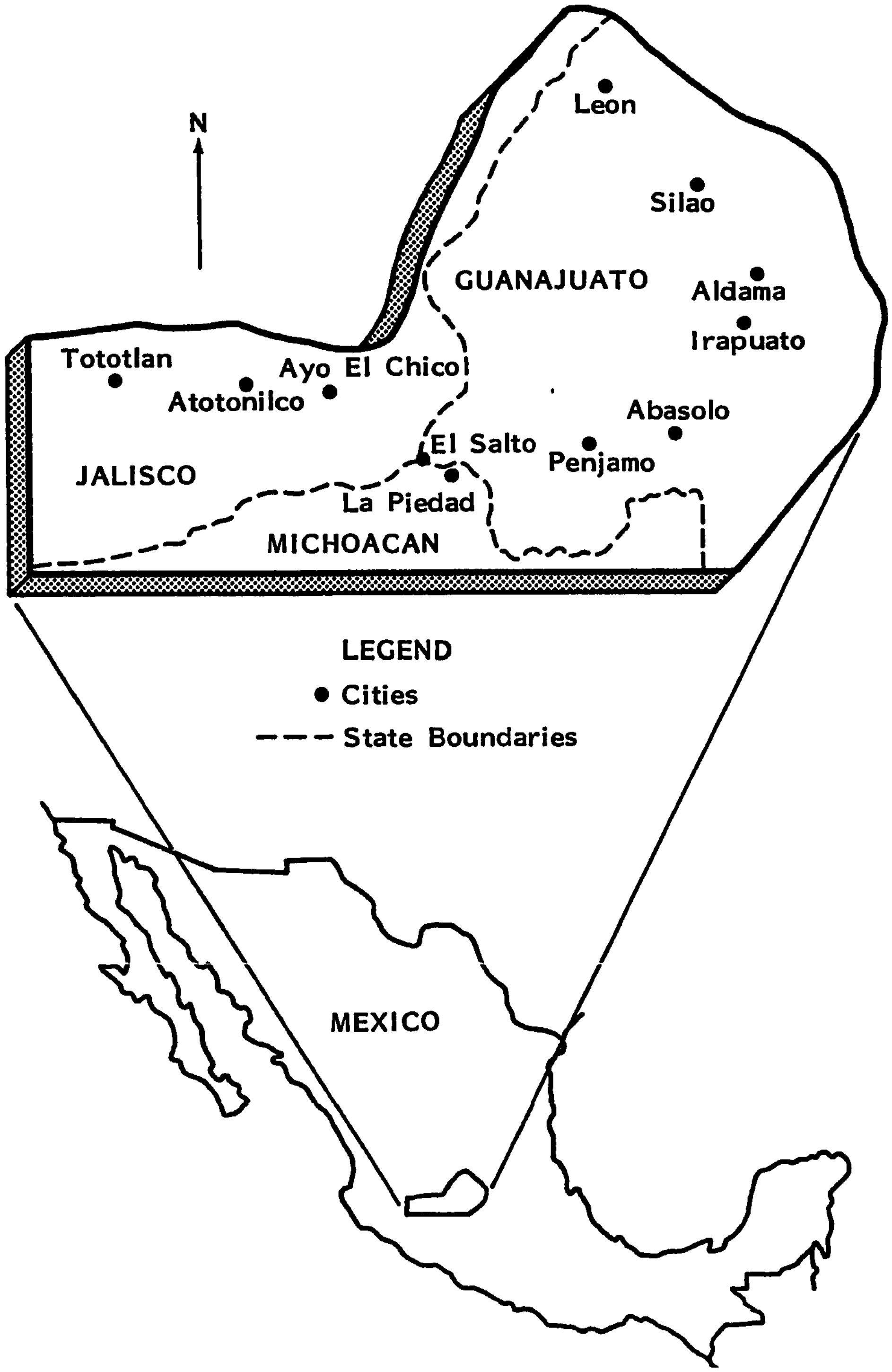

Figure 2. Geographical location of the area of study

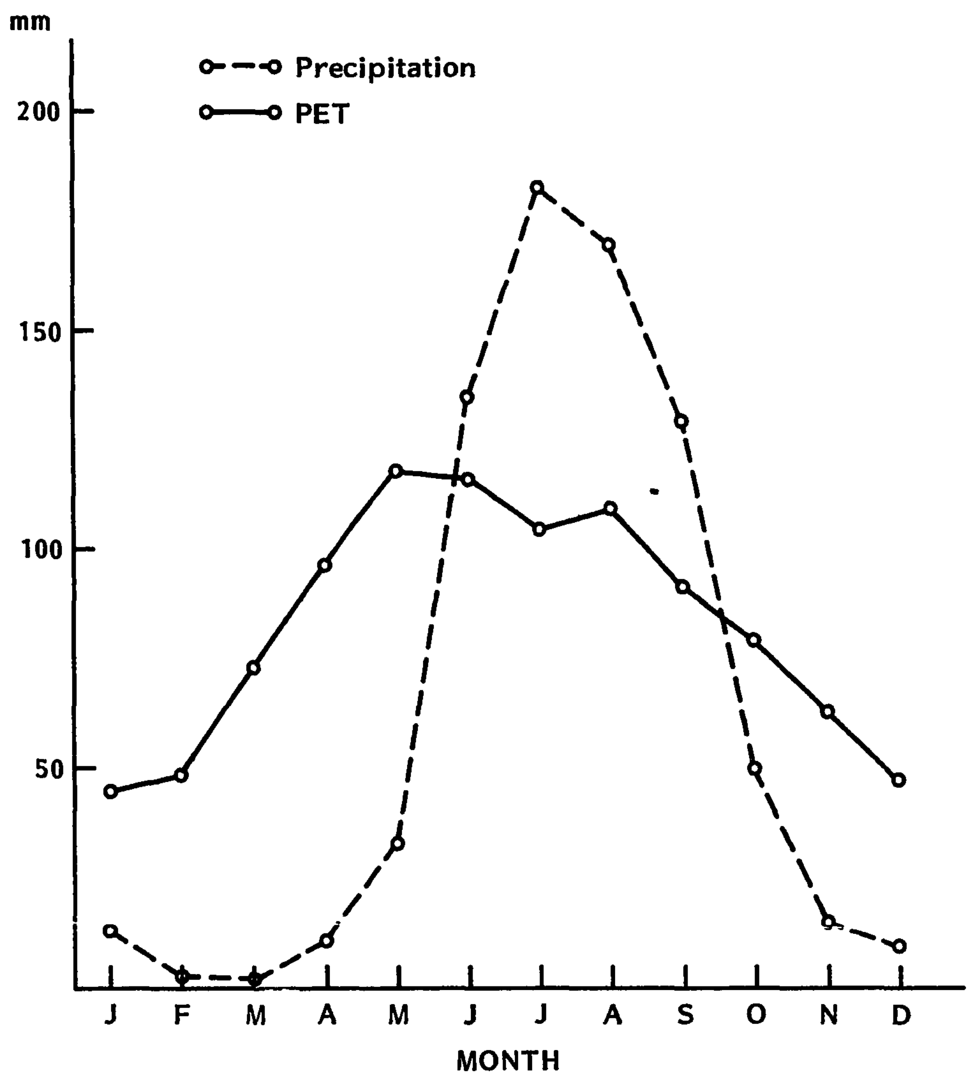

Figure 3. Average potential evapotranspiration (PET) vs precipitation, using 10 weather stations, in the area of study

months, PET is higher than precipitation, and only during the months of June through September does rainfall exceed PET. The growing season for unirrigated corn in the region goes from June to October, which is in accord with the duration of the wet season. It should be noted that, during July and August, the wettest months, the moisture surplus often becomes detrimental to crops, especially in the southernmost part of the region, where precipitation is higher and heavy-textured soils with low permeability prevail.

2. Soil characteristics

The major part of the soils in the area southwest of Abasolo (see Figure 2) are clay soils that shrink on drying and cracks form. These soils are included in the Vertisols of the Soil Taxonomy[1] of the Soil Conservation Service of the USDA (USDA, 1975). North of Abasolo the dominant soil has a sandy loam to loam texture and is brownish in color. The correct designation for this soil within this soil taxonomy is not known.

In order to give a brief characterization of the soils of the study area, analyses of samples from the plow layer and soil profile descriptions made at 77 experimental sites will be used. These soil characteristics are presented in Appendix

[1]Soil taxonomy: a basic system of soil classification for making and interpreting soil surveys.

Table A1. The pH values vary from 5.4 to 8.3 with 78% of the soils reporting values greater than 6.5. Organic matter contents were generally low with 91% of the soils having values less than 2%. Clay percentage for the plow layer varies from 9 to 67%, with 68% of the soils having values greater than 40% clay content. Fifty of the 77 experimental sites are classified as heavy-textured soils, 12 are medium-textured, and 15 are light-textured. Plant-available-water capacity, at rooting depth, estimated using texture components, varies from 37 mm to 185 mm, with 75% of the soils having less than 100 mm of storage capacity. Rooting depth varies from 25 cm to about 120 cm, with 32 (42%) of the soils having less than two feet of rooting depth. Land slope varies from 0.1 to 8% with 92% of the soils having less than 4% slope.

3. Crops

As mentioned before, rainfed corn is the most important crop in the area of study. This crop is used mainly for human consumption. Other important crops in the region are sorghum and chickpea. Sorghum is planted in summer time as an alternative crop to corn. Chickpea is planted during the fall, chiefly on clay soils, where residual moisture left by the rainy season is used to grow this crop. Both sorghum and chickpea are used in feeding animals. The use of grain sorghum is mainly in feeding poultry, whereas chickpea is used for feeding hogs.

B. Data Acquisition

Yield data used in this research came from 77 simple fertilizer trials, which were carried out with unirrigated corn in farmers' fields in the western part of the El Bajio area, during the period 1962-1965 (Laird and Rodriguez, 1965; Laird et al., 1969). The reader is referred to these sources for detailed information about the data used. In this section, only those data used in this dissertation will be mentioned.

Field experiments consisted of four levels of nitrogen fertilizer and three levels of phosphorus fertilizer. However, to test the different weather characterization approaches and to calibrate the corn-yield predicting models developed in this research, corn yields from only four treatments (0-60, 40-60, 80-60, and 120-60 kg of N and P_2O_5/ha, respectively) were used. Each treatment represented the average yield of four replications in all experiments. Corn yield data for these four treatments in the 77 experimental sites used are presented in Appendix Table A2.

Planting of the experiments in farmers' fields comprised the period between June 4 and July 7. Planting time depended on the onset of the wet season. Corn hybrids H-220 and H-230, which are well adapted to the region, were planted to give a population density of 40,000 plants/ha. Each experiment was visited about every week in order to make field observations on factors suspected of affecting corn yield.

These field observations included weed competition, leaf blight damage due to Helminthosporium turcicum, hail damage, symptoms of wilting plants, and others. The procedures followed in making these observations were described by Laird (1968). These observations, as well as others used in his research, are presented in Appendix Table A3.

To keep daily rainfall records during the growing season, rain gauges were installed near the house of the cooperating farmer and within one kilometer of the experiment. The standard rain gauge employed by the Direccion de Geografia y Meteorologia (Castillo-Mendez, 1965) was used.

In addition, during August and September at each experimental site, soil profile descriptions were made, and soil samples were taken from the different soil layers. Using soil profile descriptions, observations on rooting depths were made at this time.

C. Characterization of the Weather-Yield Relationship

As mentioned in the Literature Review, methods exist which can be used to characterize weather and its effect on crop yields. These include the use of raw meteorological variables, drought indexes, moisture-stress indexes which represent an integration of soil moisture and atmospheric demand, and plant-water status. The amount of weather data required to characterize the weather-yield relationship varies according to the method. It is expected that with more weather data a better weather characterization can be made and a better relationship between weather and yield can be obtained. In general, this is true for regions where weather is not a very limiting factor in crop production. However, where weather becomes the most limiting factor in crop yields, such as occurs in regions with low precipitation, a high correlation between single weather parameters and yields can be obtained (Wallace, 1920; Basile, 1954; Shaw, 1977). Then, the method to use will depend upon the climatic conditions of the region and the available weather data.

As mentioned earlier, the area of study presents a gradient in rainfall and basically two soil textural groups. Based on this fact, and that only limited weather data were available, it was convenient to split the region in two parts: (1) light-textured soils area and (2) clay-soils area. In doing this, it was believed that weather characterization would be easier to do because of the relatively extreme variations in soil and weather conditions prevailing in each area. The light-textured soils area is located in the eastern and northern part of the study region (Figure 2). In this part, rainfall is lower than in the area occupied by clay soils. The dominant soil has medium to light texture, and its average depth is about 60 cm. Consequently, the moisture-storage capacity for this type of soil is generally low. In the area covered by high clay content soils, precipitation is more abundant and soils are deeper than in the light-textured soils area. Due to heavy precipitation and low permeability, these soils often present drainage problems. Excess moisture may be present any time during the growing season. However, it tends to accumulate more often during the months of July and August, when precipitation is more abundant. Table A1 of the Appendix shows the experimental sites included in each portion of the area of study. A total of 53 experiments were grouped in the clay soils area, and the rest, 24, were included in the light-textured soils area. Soil profile descriptions made at each site were used in grouping experiments according to soil texture.

Weather characterization of the light-textured soils area was done according to the following approaches: (1) a soil moisture simulation model (Shaw, 1963) by which moisture stress can be computed, (2) the amount of rainfall during critical phenological periods of water deficit, and (3) a plant wilting index (Laird, 1968) which is based on visual symptoms of wilting corn plants. Likewise, in the clay soils area, the same soil-moisture simulation model with a modification to compute both excess-moisture and moisture-stress indexes, and the amount of rainfall were employed.

1. Soil-moisture simulation model

The moisture-balance method used in this research was that developed by Shaw (1963). Its computerized form was described by Dale and Hartley (1963). Modifications have been made to fit specific conditions of Iowa. The most recent ones are those made by Nielsen (1979) and Loveland (1980). The reader is referred to these sources for more details about the original method, as well as the modifications made. Following is a brief description of the original method and then the modifications made to adapt it to the area of study will be presented.

a. Description of the original model The necessary inputs to run this program are (1) the date of 75% corn silking, which is used as the base point in time to adjust for the stage of crop development, (2) the amount of water held between the wilting point and field capacity in inches for each 6-inch layer from the surface to a depth of 5 feet, (3) the initial soil moisture present above the wilting point in inches at the start of each season for each 6-inch layer, and (4) daily rainfall and class A pan evaporation during the crop season. Figure 4 shows the flow of the soil moisture model in abbreviated form. The model assumes that daily moisture extraction due to evapotranspiration occurs before infiltration of precipitation. The amount of water extracted is a function of the stage of crop development,

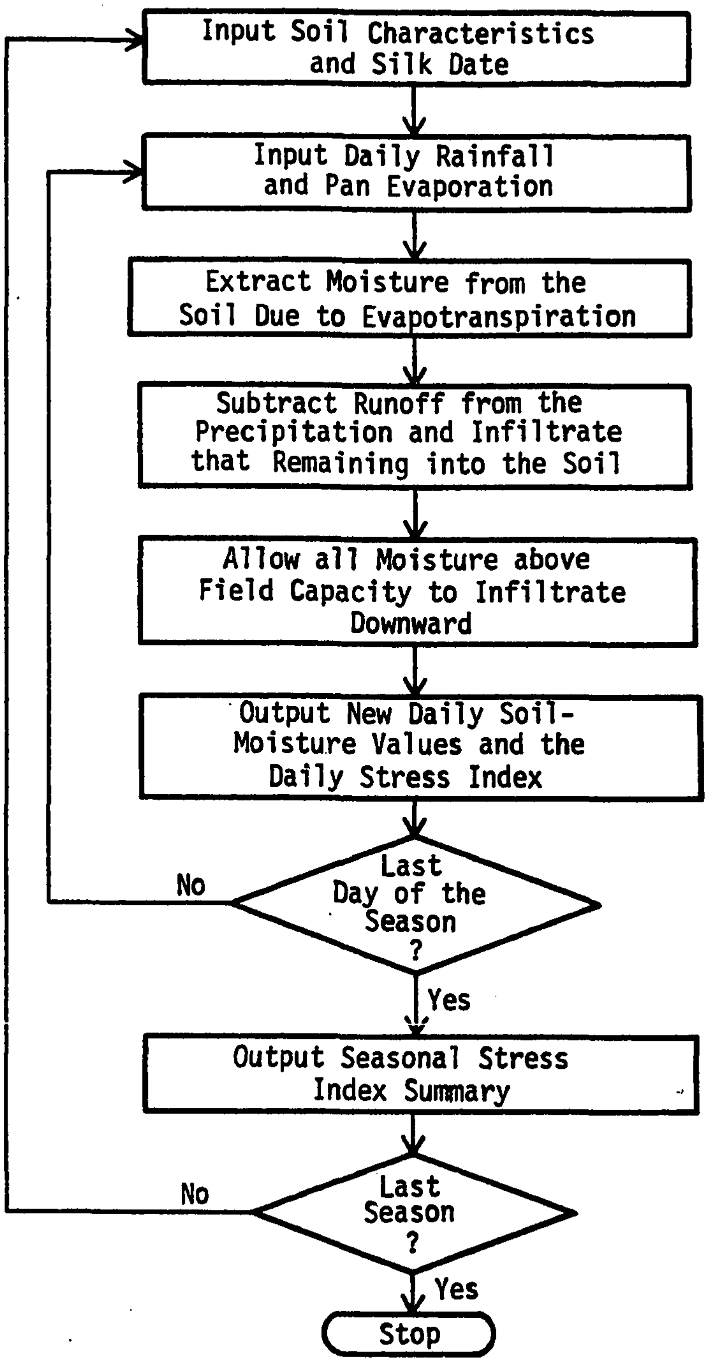

Figure 4. Generalized flow of the original simulation model (from Loveland, 1980)

the amount of soil moisture, and the atmospheric demand. Following extraction, water remaining from precipitation, after runoff has been subtracted, is infiltrated into the soil profile by filling each 6-inch layer to field capacity. In the original program, the amount of moisture is never allowed to exceed the field capacity of the soil profile. Any excess is accounted for as percolation out of the rooting depth. At the end of each day, the amount of moisture remaining, along with an index of moisture stress, are outputs. This index gives a quantitative indication of the degree of moisture deficiency.

Stress index: The extent of moisture stress for each day is computed using the following equation:

$$\text{Stress} = 1 - \frac{ET}{PET} \quad .$$

If the moisture supply can meet the atmospheric demand for water, the actual evapotranspiration (ET) is equal to the potential evapotranspiration (PET), and the stress for the day is zero. If no ET occurred, the stress would reach the maximum value of 1 for that day. On days when ET is reduced, the value can be between 0 and 1.

This index is calculated for each day of an 85-day period surrounding the silking date. The index is divided into eight 5-day periods before silking, and nine 5-day periods after the silking date. The index is then summed for each of these 5-day periods, which are weighted to account for differential sensitivity of the various stages of the corn crop to stress. The weighting factors as developed by Shaw (1974) are presented in Table 1.

The stress index also accounts for cumulative effects of severe stress that could occur. An additional weighting factor is applied whenever the stress index for two or more consecutive periods is 4.5 or greater, by multiplying the unweighted stress index by an additional 1.5. A crop failure is considered to occur whenever the 5-day unweighted index for the periods 1 before and 1 after are 4.5 or greater. Finally, all of the weighted, 5-day values are added to yield the 85-day weighted-stress index.

Account for excess moisture: The original soil-moisture model was developed for reasonably well-drained soils, where the model works well; however, in soils with slow drainage, results have been inadequate (Shaw, 1974). This is because the model dumps all moisture in excess of field capacity and saturated or nearly saturated soils conditions cannot be estimated. To overcome this, Loveland (1980) modified the infiltration and redistribution subroutine in order to assess the effect of excess moisture in soils with drainage problems. In the revised version, infiltration of daily rainfall for each 6-inch layer of the root zone is allowed to fill to saturation instead of field capacity. Under this condition, only a fraction (20 or 25% for each day, depending on rooting

Table 1. Relative weighting factors used to evaluate the effect of stress on corn yield; periods are 5-day periods relative to silking (after Shaw, 1974)

Period	Weighting factor	Period	Weighting factor
8 before	0.50	1 after	2.00
7 before	0.50	2 after	1.30
6 before	1.00	3 after	1.30
5 before	1.00	4 after	1.30
4 before	1.00	5 after	1.30
3 before	1.00	6 after	1.30
2 before	1.75	7 after	1.20
1 before	2.00	8 after	1.00
		9 after	0.50

depth) of the excess moisture is redistributed downward until field capacity is reached or resaturation is caused by rainfall again. In addition, on days in which the entire root zone is completely saturated by infiltrated rainfall, no downward redistribution is allowed. The flow chart for the redistribution subroutine as developed by Loveland (1980) is presented in Figure 5.

In using the modified infiltration and redistribution subroutine, two additional inputs are required: (1) the amount of water held between the wilting point and saturation in

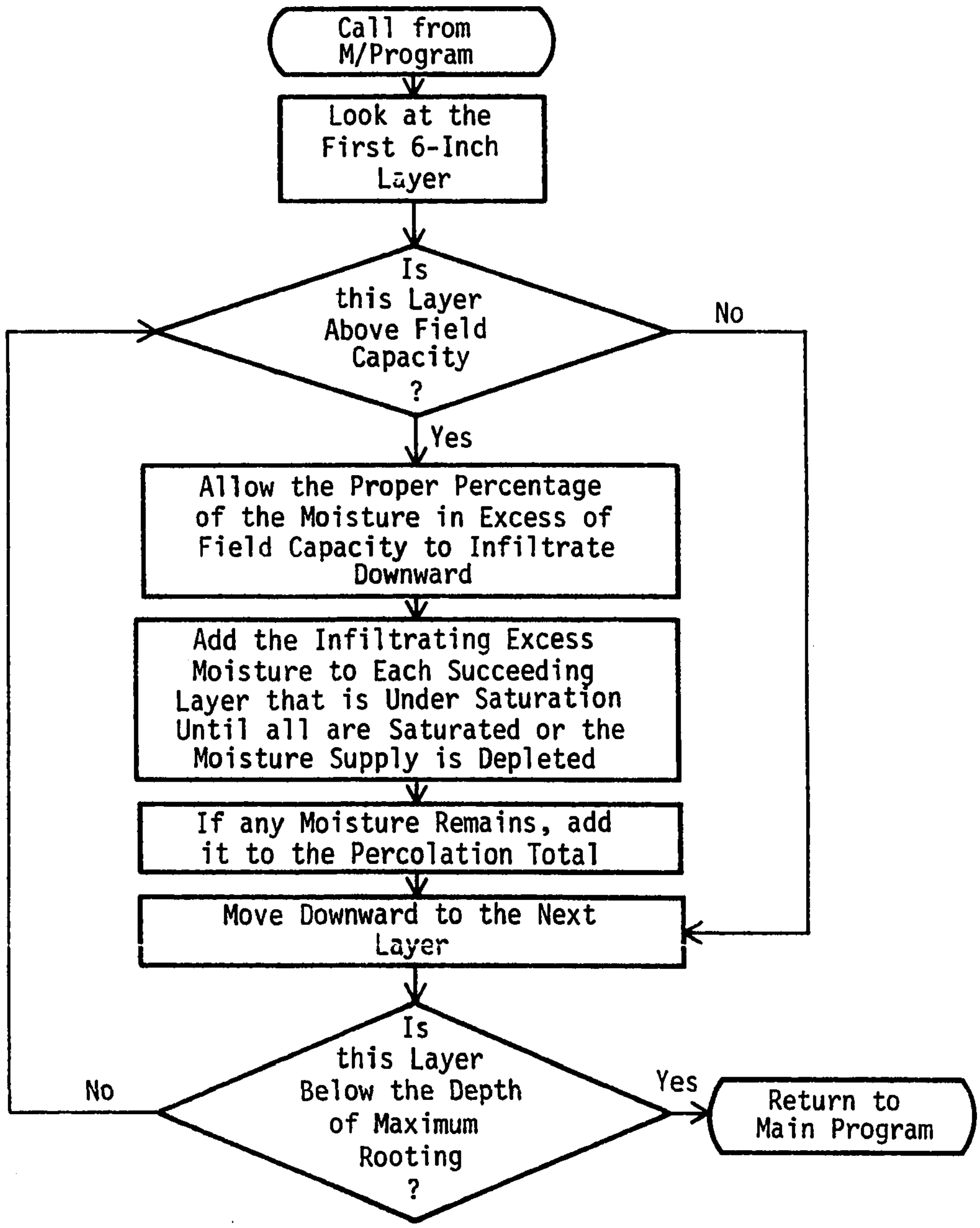

Figure 5. Generalized flow of the redistribution subroutine to account for excess moisture (from Loveland, 1980)

inches, for each 6-inch layer from the surface to a depth of 5 feet, and (2) the amount of water held between wilting point and complete saturation of the total pore space (TPS) in inches for each of the top two 6-inch layers. The second input is necessary for the computation of an index of excess moisture. It should be noted that with the revised version it is possible to compute both moisture stress and excess moisture indexes simultaneously.

b. Modifications To adapt the soil moisture simulation model to the area of study in central Mexico, modifications of the following were made: (1) silking date, (2) plant available water capacity, (3) starting soil moisture, (4) rooting extraction schedule, (5) evaporation rate for the top 6-inch layer, and (6) excess moisture index. Modifications 1 to 5 were made to the original model, which was employed in the light-textured soils area. All modifications but number 5 were also made to the revised soil-moisture model, which, in turn, was used to evaluate excess moisture and moisture deficits in the clay soils.

Silking date: Silking date was changed from July 31 (average 75% corn silking date for Iowa) to September 3, which was the average silking date for corn grown during the 4-year period in the area of study. All steps involving silking date in the computerized program were adjusted to fit the new date. It should be noted that silking date is used as the base point in time to adjust for the stage of crop development. Values for silking date are presented in Appendix Table A3.

Reestimation of available soil moisture: There is evidence that the amount of available soil moisture may be different depending upon the method used for its determination. Shaw and Runkles (1956) compared the 1/3-bar moisture percent vs the field capacity method. They found good agreement for the two methods for gravimetric water contents between 18 and 32%. Above 32%, the 1/3-bar method overestimated the field capacity. Based on this, they concluded that considerable error could be involved in estimating available soil moisture if 1/3-bar estimates were used. Young and Dixon (1966) attributed this overestimation to the use of sieved soil samples. They showed that sieved samples from soils having more than 35% clay tend to overestimate available soil moisture. This overestimation, as explained by these researchers, is caused by an increase in pores of a size that can hold water against 1/3-bar suction. They concluded that more reliable estimates of available soil moisture can be obtained if both the moisture weight percentage and the bulk density values are obtained by using undisturbed samples.

Since plant-available-water capacity is an important factor in determining stress index and because field capacity (FC) originally was determined mainly by using the 1/3-bar method, it was decided to reestimate available soil moisture using alternative methods. Table 2 shows five approaches used to estimate available soil moisture. Four of these approaches were based on the use of texture components. In approach nos. 1, 2, 4 and 7, available soil moisture (ASM) was estimated as the difference in soil moisture between FC and wilting point (WP). In approach no. 1, FC and WP were mainly determined by using lab methods, although in a few experimental sites, a small plastic cylinder and the sunflower plant were used to estimate FC and WP, respectively. In approach nos. 2 and 4, the clay percent was used to estimate FC and WP by using linear regression equations developed by Unger (1975) and by the author, respectively. Available soil moisture in approach no. 5 was estimated by using a graphical method (Figure 6) developed by L. C. Dumenil (Department of Agronomy, Iowa State University, Ames, Iowa, personal communication). And finally, in approach no. 7, FC was estimated by the same equation as in approach no. 4, and a graphical method (Figure 7) developed by Nielsen and Shaw (1957) was used to estimate WP.

Available soil moisture by volume for each 6-inch layer of the rooting zone was obtained using the following formula:

$$ASM = (FC - WP)/100 \times D_B \times 6 \quad .$$

The bulk density (D_B) values used for this computation are given in Appendix Table A1. A single value of D_B was used for the entire soil profile.

Table 2. Approaches used to estimate plant-available-water capacity for soils of the area of study

Approach no.	Field capacity (FC)	Wilting point (WP)	Available soil moisture
1	FC = 1/3 bar	WP = 15 bars	FC - WP
2	FC = 6.91 + 0.753*CLAY[a]	WP = 1.78 + 0.629*CLAY[a]	FC - WP
4	FC = 8.56 + 0.671*CLAY[b]	WP = 2.17 + 0.432*CLAY[b]	FC - WP
5			Soil texture components[c]
7	FC = 8.56 + 0.671*CLAY	WP = clay percent[d]	FC - WP

[a]Equations determined by Unger (1975) for Texas soils.

[b]Equations determined in this research using soils of the area of study.

[c]Graphical method developed by L. C. Dumenil (Department of Agronomy, Iowa State University, Ames, Iowa) for Iowa soils.

[d]Graphical method developed by Nielsen and Shaw (1957).

Adjustment for sand size -- loamy sand and sandy loam	
Coarse	-0.01 in/in
Medium	0.00 in/in
Fine	+0.01 in/in
Very Fine	+0.05 in/in

Adjustment for O.C. content	
% O.C.	Adj. (in/in)
0.0	-0.01
1.0	0.00
2.0	+0.01
3.0	+0.02
4.0	+0.03
5.0	+0.04

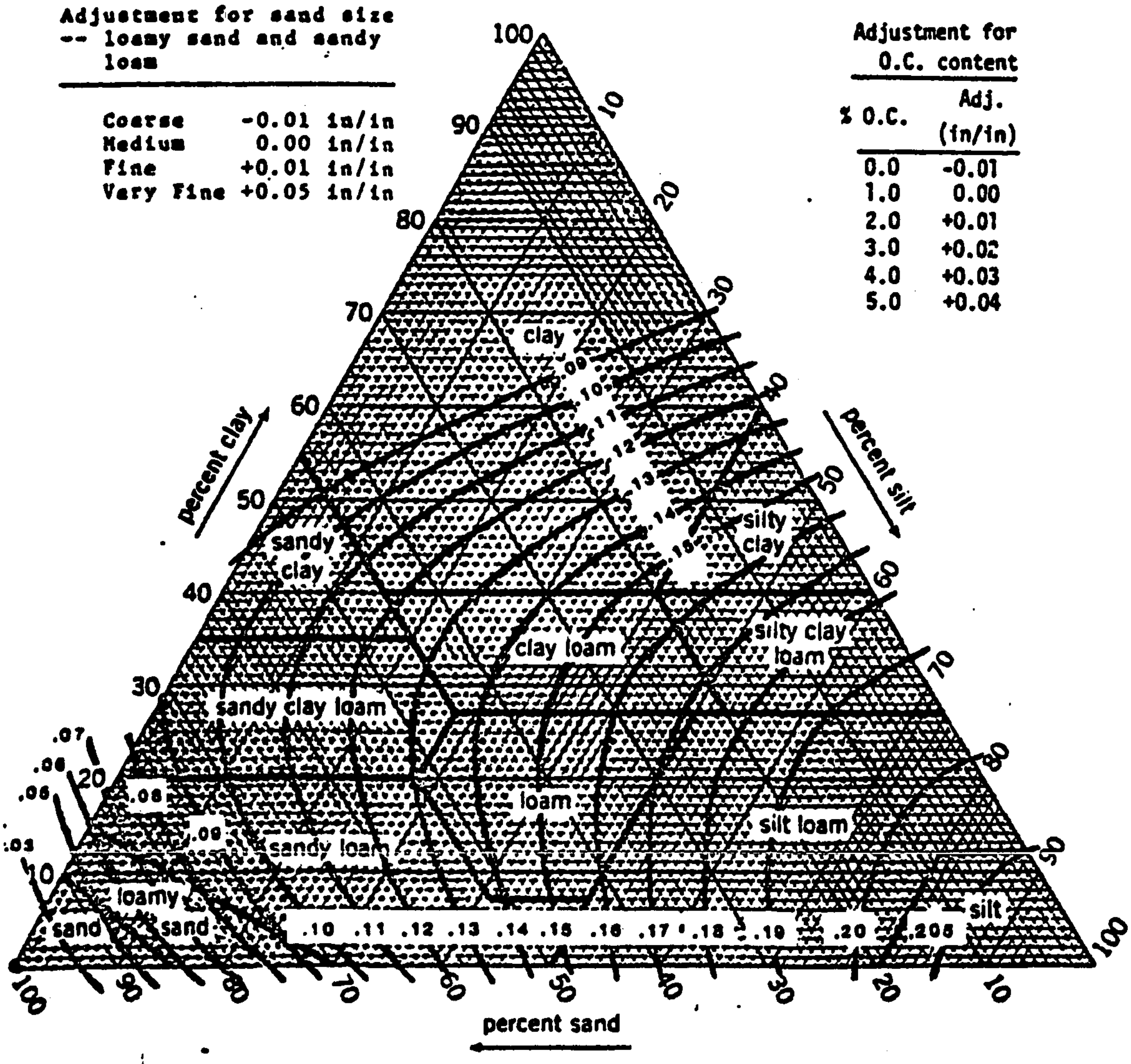

Figure 6. Estimated relationship between plant available water capacity (PAWC) and soil texture components (rev. 1-11-78, Dumenil and Fenton)

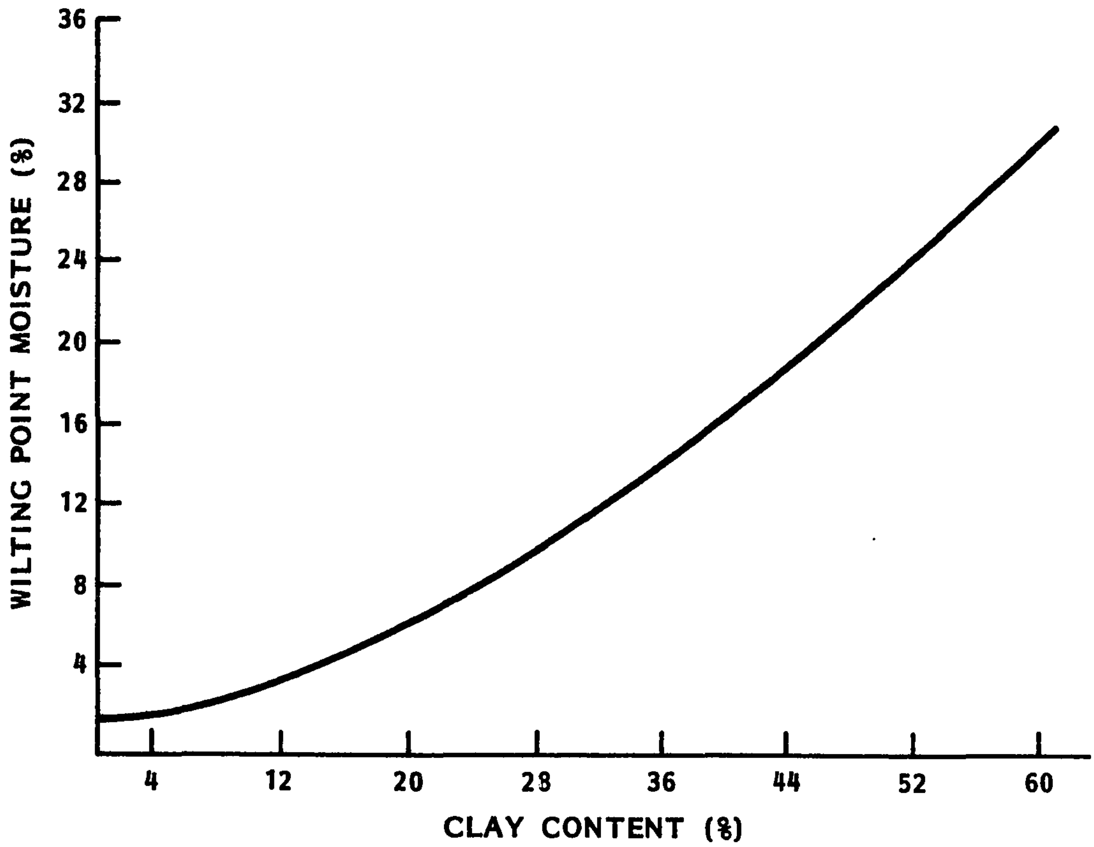

Figure 7. Wilting point moisture percentage prediction from clay content as determined by hydrometer method; based on 730 samples from Iowa soils (from Nielsen and Shaw, 1957)

Starting soil moisture: As mentioned earlier in this chapter, the climate of the area of study is characterized for having a dry and a rainy season. In addition, corn is planted usually shortly after the first heavy rainfall. Soil-moisture measurements made shortly before planting at many sites during 1962 and 1963 were found to be near or below wilting point (Laird and Rodriguez, 1965). Based on this, starting soil moisture equal to zero was used in the soil moisture simulation program.

Rooting extraction schedule: Since maximum rooting depth was observed to be quite variable in the 77 experimental sites, the original extraction pattern was modified to fit these rooting depths, which ranged from 25 cm to 120 cm. The original model was designed for a 5-foot root zone. In order to adapt the rooting extraction schedule to the different rooting depths, it was necessary to be able to run the simulation program for the various depths observed. This was done by inserting zeros on the field capacity, saturation, and starting soil-moisture input cards for all 6-inch layers below the depth of maximum rooting. This assured that no moisture was extracted below the rooting depth and, instead, any attempted extraction below that depth was equally divided among layers of the actual root zone. Table 3 gives the original water extraction by corn from the soil profile as prepared by Shaw (1963). Table 4 shows the modified

Table 3. Original water extraction from the soil profile expressed as the percent of the total transpiration which comes from respective layers during the growing season (after Shaw, 1963)

Date	6-inch thick respective layers numbered from the surface									
	1	2	3	4	5	6	7	8	9	10
To June 7	100.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
June 8 to June 14	50.0	50.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
June 15 to June 27	33.3	33.3	16.6	16.6	0.0	0.0	0.0	0.0	0.0	0.0
June 28 to July 4	30.0	30.0	10.0	10.0	20.0	0.0	0.0	0.0	0.0	0.0
July 5 to July 11	30.0	30.0	10.0	10.0	10.0	10.0	0.0	0.0	0.0	0.0
July 12 to July 18	30.0	30.0	7.5	7.5	7.5	7.5	10.0	0.0	0.0	0.0
July 19 to July 25	30.0	30.0	7.5	7.5	7.5	7.5	5.0	5.0	0.0	0.0
July 26 to August 1	30.0	30.0	5.0	5.0	5.0	5.0	5.0	5.0	10.0	0.0[a]
	30.0	30.0	7.5	7.5	7.5	7.5	5.0	5.0	0.0	0.0[b]
After August 1	30.0	30.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0[a]
	30.0	30.0	7.5	7.5	7.5	7.5	5.0	5.0	0.0	0.0[b]

[a]Used only if the first 4 feet all have less moisture than 50% of their available water-holding capacity.

[b]Used if any of the first 4 feet have more moisture than 50% of their available water-holding capacity.

Table 4. Modified water extraction from the soil profile expressed as the percent of the total transpiration which comes from respective layers during the growing season

Date	6-inch thick respective layers numbered from the surface							
	1	2	3	4	5	6	7	8
To July 10	100.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
July 11 to July 17	50.0	50.0	0.0	0.0	0.0	0.0	0.0	0.0
July 18 to July 24	40.0	40.0	20.0	0.0	0.0	0.0	0.0	0.0
July 25 to July 31	33.3	33.3	16.6	16.6	0.0	0.0	0.0	0.0
Aug 1 to Aug 7	30.0	30.0	10.0	10.0	20.0	0.0	0.0	0.0
Aug 8 to Aug 14	30.0	30.0	10.0	10.0	10.0	10.0	0.0	0.0
Aug 15 to Aug 21	30.0	30.0	7.5	7.5	7.5	7.5	10.0	0.0
After Aug 21	30.0	30.0	7.5	7.5	7.5	7.5	5.0	5.0

water-extraction schedule adapted to fit observed rooting depths from about 1 foot to 4 feet in the area of study.

Evaporation rate: The evaporation rate for the top 6-inch soil layer, early during the vegetative stage of corn, is set in the original soil moisture program as 0.10 inch per day. Since in the area of study the highest pan evaporation rates are experienced during May and June, this rate was increased from 0.10 to 0.15 inches per day in order to account for this factor in the moisture stress index estimation. This modification was made for approaches nos. 5 and 7 presented in Table 2. This gave a total of seven moisture stress indexes to be tested in the light-textured soils. Symbols assigned to these approaches were MS1, MS2, MS4, MS5, MS5E, MS7, and MS7E, which correspond to the approaches used to estimate available soil moisture and to the modification made in evaporation rate.

Excess-moisture index: In order to estimate the effect of excess moisture on corn yields through an index, in the clay soils area, the revised version of the soil-moisture model was used. It was assumed that excess moisture caused by heavy rainfall, along with low soil permeability, could reasonably be estimated by using the modified redistribution subroutine, designed for soils with drainage problems.

As mentioned earlier, in using the modified infiltration and redistribution subroutine, two additional inputs are required: (1) the amount of water held between wilting point and saturation, in inches, for each 6-inch layer from the surface down to rooting depth; saturation is assumed to occur when the soil pore space is 90% water filled, with the exception of the top 6-inch layer, where saturation is assumed to occur at 85% because aeration is increased by tillage operations in that layer; and (2) the amount of water held between the wilting point and complete saturation of the total pore space in inches for each of the top two 6-inch layers.

In order to derive the necessary soil characteristic inputs, it was necessary to estimate the total porosity, field capacity and wilting point values. These were required for each 6-inch layer down to the maximum rooting depth observed in each experimental site.

Total porosity values were attained from the formula:

$$TP = 1 - D_B/D_P \quad ,$$

where TP is total porosity, D_B equals the bulk density, and D_P is particle density, which was assumed to be 2.65 g/cc.

Field capacity values were obtained using a method based on texture components (Figure 6), which was developed by L. C. Dumenil (Department of Agronomy, Iowa State University, Ames, Iowa, personal communication).

Wilting point (WP) values were computed by using the following regression equation:

$$WP = 2.17 + 0.432 * \text{clay percent} \quad .$$

This equation was developed using soil samples from the area of study as an alternative method to estimating WP in addition to those presented in Table 2.

Once total porosity, field capacity and wilting point values were determined, the necessary soil characteristic inputs were calculated. The amount of water held between the wilting point and complete saturation for a 6-inch layer was computed as follows:

$$TPS = ((TP - WP)*6)/100 \quad ,$$

where TPS is total pore space and TP and WP are total porosity and wilting point expressed as percent, respectively.

To compute the water held between the wilting point and 90% or 85% of the total pore space for a 6-inch layer, the same formula was used with the exception that TP values was previously multiplied by .90 or .85.

Air space expressed as a percentage of the total soil volume for a 6-inch layer can be found by:

$$\text{Air space} = ((TPS - WP) - (SM - WP))/6*100 \quad ,$$

where SM is soil moisture at field capacity.

From this equation, the excess-moisture index equals the average of the air space values for the top two 6-inch layers. Air space values less than or equal to 10% of the total soil volume are assumed to have detrimental effects on growth and development of crops, as shown in the literature review on excess moisture. However, this critical level may vary according to soil and plant conditions. Based on this, 7, 10 and 13% aeration levels were tested using a 108-day period beginning 3 days after planting. Excess-moisture indexes for these 3 aeration levels equaled the number of "wet days" in which air porosity was equal or below the level established for each index. Since excess moisture may have a different effect on yield, depending on the growing stage of the crop, as discussed in the literature review section, the best aeration level was further tested. This was done by dividing the 108-day period into eighteen 6-day periods in order to find the critical period of excess moisture.

Other inputs required in estimating moisture-stress and excess-moisture indexes for corn, such as runoff estimation, evapotranspiration/pan evaporation ratio through the growing season, and relative rate of transpiration, remained the same as in the original simulation model. No attempt was made to change these factors because of limitations of available data. It is admitted that the extrapolation of these three factors to an area different than Iowa is a serious limitation for the success of this method. However, this extrapolation is less if the following is considered. (1) More than 90% of the experimental sites in the area of study have land-slope values less than 4%, thus reducing the need for a change in runoff estimation. (2) The average growing period for corn hybrids used in the area of study is very similar to those grown in

Iowa (125 days on the average). Although it is admitted that the duration of time between different stages of development may vary with latitude, it is also expected there would be little variation in the ET/Evap ratio between the regions. (3) Since the rate of actual transpiration by corn, employed in the simulation program, was determined using a silty clay soil, the use of this information for medium-textured and clay soils is believed to be not so critical, although it is recognized that the rate of transpiration may vary due to differences in solar radiation regimes for the two regions.

2. Rainfall

Rainfall amounts during critical phenological periods were used as an alternative weather approach to characterize both moisture deficits in light-textured soils, and excess moisture in clay soils.

The procedure used in the light-textured soils area was to divide the corn growing season into 5-day periods, using the silking date as the reference point. Total amounts of rainfall for twelve 5-day periods before silking and ten 5-day periods after silking were then computed. The next step consisted of computing the simple correlation coefficient between rainfall amounts for a number of combinations, including periods before and after silking, and corn yields. The critical phenological period of moisture deficit for corn, using this iterative procedure, was determined by the highest correlation between the rainfall period and corn yields.

In the clay soils area, a similar procedure to determine the critical period of excess moisture for corn, using rainfall amounts, was employed. In doing this, the planting date was used as the base point, instead of silking date. This is because detrimental effects caused by excess moisture are larger in the vegetative stage than in the reproductive one, as discussed earlier in the literature review section on excess moisture. In addition, the corn-growing season was divided into 6-day periods instead of 5-day periods as used before. The critical period of excess moisture for corn, using an iterative process, as mentioned above, was given by the highest correlation between the rainfall period and corn yields.

3. Visual symptoms of plant wilting

Ideally, the best method to characterize moisture stress in crops would be the plant-water status. This is because it represents an integration of the atmospheric demand, soil-water potential, rooting density and distribution, as well as other plant characteristics (Kramer, 1969). Based on this, a number of methods have been developed to measure the status of water in the plant. A method based on visual symptoms of plant wilting was used in this research. This technique was developed by Laird (1968) who used the same experimental data employed in this dissertation. However, at the time when the experiments used in this dissertation were carried out (1962-1965), the method he employed to record visual symptoms of plant wilting was much simpler. Each experiment was visited about every week and observations on wilting were made. Each day during which symptoms of wilting were observed in any part of the experiment was considered to be a "drought day". On days when wilting had begun one or more days earlier, the date of initiation of wilting was estimated.

Using this simple procedure, the number of days with wilted plants was recorded from shortly after emergence of plants until the physiological maturity of the crop. In this dissertation, however, only the number of days with wilted plants in a 70-day period was considered. This seasonal "wilting plant index" (WPI) included 40 days before silking and 30 days after silking.

4. Evaluation of weather approaches

The approaches used to characterize the relationship between weather and yield in the two soil groups were tested using correlation and regression techniques. When the regression technique was employed, the weather approaches were tested by computing a series of regressions using a nitrogen fertilizer model previously developed as the base model. The approaches to be tested were added one at a time to the base model and the regression computed. The criterion used to select the best approach was the largest increase in the R^2

of the regression.

D. Development of Corn-Yield Models

In addition to the applied nitrogen fertilizer and the weather factor, additional soil, management and environmental variables were included in developing corn-yield regression models for the area of study. In the light-textured soils area, three yield models were developed, one for each weather characterization approach used. In the clay soils, only two yield models were developed, one for each approach used. The Statistical Analysis System (Barr et al., 1979) was used in developing and testing these models.

Tables 5 and 6 show symbols, means, and ranges for the variables used in developing corn-yield models. Codification for WEED, H, L and ROT variables remained the same as that used by Laird et al. (1969) in an earlier report.

In building yield models for the light-textured and clay soils areas, the same statistical procedure was employed. This consisted, first, in computing the simple correlation coefficients between yield, the dependent variable, and independent variables, and between independent variables. Tables 7 and 8 show these correlations for the light-textured soils and for the clay soils area, respectively. Correlation coefficients between yield and independent variables, and between independent variables can be useful in two ways: (1) to detect

Table 5. Symbols, codification, means, and ranges for the variables used, light-textured soils area

Symbol	Variable	Mean	Range
YIELD	Corn yield, kg/ha	3189	700-5380
ROOT	Rooting depth, cm	57.7	25-120
SLO	% land slope at site area x 10	21	20-80
SN	% total soil nitrogen in plow layer x 1000	83	46-124
V	Hybrid corn, dummy variable	0.96	0-1
WEED	Weed competition, coded 0 to 6 x 10	5.8	0-30
H	Hail damage, coded 0 to 6 x 10	4.2	0-30
L	Leaf blight infestation, coded 0 to 7 x 10	5	0-10
PH	Soil reaction in the plow layer x 10	66	54-83
OM	% organic carbon in the plow layer x 10	11.2	5.7-19.0
CLAY	% clay in the plow layer	18.9	9-35
ROT	Crop rotation, coded 10 to 40	30.4	10-40
SILK	Number of days from planting to 75% silking	76	68-83
PAWC7	Plant available water capacity at rooting depth, in mm of H_2O	135	63-250
MS7	Moisture stress index	8.7	0-39.5
R80	Rainfall in mm for the 80-day critical period around silking date	419	182-640
WPI	Wilting plant index, based on wilting corn plants	11.5	0-37
N	Applied nitrogen fertilizer, kg/ha	60	0-120

Table 6. Symbols, codification, means, and ranges for the variables used, clay-soils area

Symbol	Variable	Mean	Range
YIELD	Corn yield, kg/ha	2017	250-6480
ROOT	Rooting depth, cm	82.2	40-120
SLO	% land slope of site area x 10	16.7	1-80
SN	% total soil nitrogen in the plow layer x 1000	86	47-137
V	Hybrid corn, dummy variable	0.58	0-1
WEED	Weed competition, coded 0 to 6 x 10	8.5	0-60
H	Hail damage, coded 0 to 6 x 10	4.2	0-50
L	Leaf blight infestation, coded 0 to 7 x 10	12.5	0-70
PH	Soil reaction in the plow layer x 10	71.4	62-82
OM	% organic carbon in the plow layer x 10	15.8	8.1-24.7
CLAY	% clay in the plow layer	56.6	37-67
ROT	Crop rotation, coded 10 to 40	32.6	10-40
SILK	Number of days from planting to silking date	76.5	63-87
PAWC5	Plant available water capacity at rooting depth in mm of H_2O	85.7	39-185
MS52	Moisture stress index	2.25	0-33
EM54	Excess moisture index	37.2	16-54
R48	Rainfall in mm for a 48-day period after 12 days of planting	325	124-605
R30	Rainfall in mm for a 30-day period around silking date	166	54-312
N	Applied nitrogen fertilizer, kg/ha	60	0-120

Table 7. Simple correlation coefficients between yield and independent variables (n=80), and between independent variables (n=20), light-textured soils area[a]

Between variables		r	Between variables		r
YIELD and	ROOT	.34**	OM and	CLAY	.43
	SN	.24*			
	H	-.25*	CLAY and	PAWC	.37
	PH	.11			
	OM	.11	PAWC7 and	SLO	-.57**
	CLAY	.18		MS7	-.37
	SILK	.11		V	.36
	PAWC7	.38**		WEED	-.32
	MS7	-.37**		WPI	-.41
	R80	.46**			
	WPI	-.54**	MS7 and	WEED	-.32
	N	.50**		WPI	.77**
				R80	-.71**
ROOT and	SLO	-.55*			
	MS7	-.33	R80 and	WPI	-.83**
	V	.39			
	WEED	-.33	SLO and	V	-.74**
	WPI	-.46*		WEED	.55*
	PAWC7	.92**			
	SILK	.35	V and	WEED	-.76**
	R80	.35			
			WEED and	ROT	-.65**
SN and	OM	.81**			
H and	L	-.38			
	SILK	.31			
PH and	SLO	-.37			
	CLAY	.62**			
	PAWC7	.42			

[a]Only the correlation with YIELD greater than ±.10 and those between the other variables greater than ±.30 are listed.

**,*Significant at the 1% and 5% levels, respectively.

Table 8. Simple correlation coefficients between yield and independent variables (n=180) and between independent variables (n=45), clay-soils area[a]

Between variables		r	Between variables		r
YIELD and	SN	.14	L and	R48	.44**
	V	.13		R30	-.33*
	WEED	-.17*		PAWC5	.45**
	H	-.17*			
	L	-.19**	CLAY and	PAWC5	-.45**
	OM	.16*			
	SILK	-.27**	SILK and	EM54	.37*
	EM54	-.30**		R30	-.38*
	R48	-.30**			
	R30	.24**	EM54 and	R48	.67**
	N	.77**		R30	-.45**
MS52 and	EM54	-.37**	R48 and	R30	-.52**
ROOT and	SLO	-.27			
	PAWC5	.87**			
SLO and	SN	.41**			
	WEED	.42**			
	OM	.33*			
	SILK	.44**			
	PAWC5	-.30*			
SN and	OM	.74**			
	R48	.30*			
V and	L	-.38*			
	ROT	.34*			
	R48	-.32*			
WEED and	ROT	-.35*			

[a]Only the correlation with YIELD greater than ±.10 and those between the other variables greater than ±.30 are listed.

**,*Significant the 1% and 5% levels, respectively.

potential-predicting variables for corn yields in the first case, and (2) to know the degree of correlation between independent variables in the second. The intercorrelations among independent variables have to be considered because they affect the estimation and interpretation of the effects of individual variables and restrict the use of the developed models (Pena-Olvera, 1979). In order to reduce the intercorrelation problems between independent variables, a correlation coefficient $\geq$ than ± 0.55 was established. This means that, if the correlation coefficient between two variables is equal to or higher than ± 0.55, one of these variables was deleted.

Second, for the variables left after the correlation screening, the quadratic effect of some variables, as well as some simple (linear by linear) interactions, were generated as additional variables to be selected. In doing all this, a criterion based on agronomic considerations was employed. To approximate the effect of independent variables on yield, a quadratic function was used. These variables were coded by subtracting their minimum value in order to represent their effect on yield above that of the minimum observed value.

Finally, in order to arrive at the final model for each weather approach, a 5% level of significance was established for the variables that should be included in each of these multiple regression models.

E. Evaluation of Yield-Predicting Models

In order to evaluate the accuracy of the corn yield predictions of the five yield models developed in this study, independent yield data were used. In the light-textured soils, a total of 16 yield observations from four experiments selected at random were used. About 17% of the original data were used for this testing. On the other hand, since the clay soils area included more experiments, 32 observations from 8 experiments, also selected at random, were used. In this case, the yield data omitted for testing the models included about 15% of the original data.

Yield-predicting models were evaluated using the differences between predicted yield and actual yield according to some of the criteria suggested by Wilson and Sebaugh (1981). These criteria included bias, relative bias, standard deviation, relative standard deviation, range, and the correlation coefficient between actual and predicted corn yields. The formula used to compute these indicators of yield reliability were the following:

$$\text{Bias} = B = 1/n \, \Sigma di = \bar{d} \quad ,$$

where $di = \hat{Y}i - Yi$ = difference between predicted and actual yield, respectively, for observation i,

where $i = 1, \ldots, n$ = number of test observations.

$$\text{Relative bias} = RB = 100 \, B/\bar{Y} \quad ,$$

where $\overline{Y} = 1/n\ \Sigma Yi$ = average actual yield .

Standard deviation = SD = $(Var)^{1/2}$,

where variance = var = $1/n\ \Sigma(di - \overline{d})^2$.

Relative standard deviation = RSD = 100 SD/$(\overline{Y} + \overline{d})$.

Correlation coefficient r between $\hat{Y}i$ and Yi, where

$$r = \frac{\left[\Sigma \hat{Y}i Yi - \frac{(\Sigma \hat{Y}i)(\Sigma Yi)}{n}\right]}{\left[(\Sigma \hat{Y}i^2 - \frac{(\Sigma \hat{Y}i)^2}{n})(\Sigma Yi^2 - \frac{(\Sigma Yi)^2}{n})\right]^{1/2}} .$$

Since the yield observations used in evaluating regression models came from four fertilizer treatments tested in each experiment, an additional evaluation for corn-yield differences between estimated and actual yield was made. A variance component method for these differences was employed in order to estimate the variance component between experimental sites and within experiments.

The analysis of difference between actual and estimated yield for the five corn-yield models developed in this study was as follows:

Source	d.f.	Expected mean square
Between experimental sites	s-1	$\sigma_W^2 + t\sigma_B^2$
Within experimental sites	s(t-1)	σ_W^2
Total	n-1	

The yield difference (DIF) between actual and predicted yield consists of two components, experimental sites (s) plus treatments (t) within experimental sites. This can be expressed as:

$$DIF = \sigma_B^2 + \sigma_W^2 \quad ,$$

where σ_B^2 = variance component between sites and

σ_W^2 = variance component within sites.

Using this procedure to analyze yield differences caused by two sources of variation, it is expected that, as the variance component within sites (σ_W^2) increases, corn yield predictions made by a model, will be more precise. This is simply because the larger variation in corn yields is due to the different N fertilizer levels employed in these experiments.

F. Rainfall Probabilities

Since a yield model including the rainfall variable was used in determining optimum N rates and corn yields using simulation techniques, a brief description of the method used to compute rainfall probabilities is given.

The gamma distribution was used to compute rainfall probabilities. This distribution has been found to give good fits to precipitation climatological series (Thom, 1966). It is defined by its frequency or probability density function:

$$f(X) = \frac{1}{\beta^{\alpha}\Gamma(\alpha)} X^{\alpha-1} e^{-X/\beta} ,$$

where β is a scale parameter, α is a shape parameter, and $\Gamma(\alpha)$ is the gamma function of α.

To fit this distribution, it is necessary to estimate β and α. These parameters were estimated using Thom's maximum likelihood method as described by Haan (1977). The procedure is as follows:

$$\hat{\alpha} = (1 + \sqrt{1+4y/3})/4y ,$$

where $y = \ln \overline{X} - \overline{\ln X}$ and

$$\hat{\beta} = \hat{\alpha}/\overline{X} .$$

The maximum likelihood estimator for $\hat{\alpha}$ may be corrected for bias using the following equation:

$$E(\hat{\alpha} - \alpha) = 3\,\hat{\alpha}/n \quad \text{and}$$

therefore:

$$E(a) = \alpha - E(\hat{\alpha} - \alpha) .$$

The distribution function from which rainfall probabilities may be obtained is:

$$Px(X) = \int_{o}^{x} \beta^{\alpha} X^{\alpha-1} e^{-\beta X}/ (\alpha)\, dx ,$$

which can be evaluated using a table of the incomplete gamma function. Pearson and Hartley (1954) presented tabulated values for this function in "Biometrika Tables for Statisticians," Vol. 1.

This table contains 1 - Px(X). The table is entered with:

$$\chi^2 = 2\beta X \quad \text{and} \quad \nu = 2\alpha \quad .$$

Using this procedure, rainfall probabilities were computed for several locations in the area of study, where a climatological rainfall series of 31 years was used.

G. Simulation of Optimum N Rates and Corn Yields

The procedure used to compute economic optimum rates of N fertilizer was that presented by Heady (1956). The optimum level of N fertilizer is defined by the following equation:

$$\partial Y/\partial N = P_n/P_y \quad ,$$

where $\partial Y/\partial N$ is the marginal yield or response, and P_n/P_y is the price ratio (price per unit of fertilizer divided by the price per unit of yield). The marginal yield is the first derivative of yield with respect to N. Under no capital limitations, the solution for optimum N fertilizer rates is obtained simply by equating the first derivative of the yield equation with respect to N, to the inverse price ratio. In this study, the optimum N rate was calculated for conditions of limited capital because of the high year-to-year weather variability, small land holdings and capital limitations of farmers in the area, among other factors.

In computing optimum N rates under limited capital, an arbitrary return rate of $2.00 was selected. This represents the rate of N application where the last dollar invested on N fertilizer must return $2.00 worth of grain before farmers will risk the expenditure. This restricted optimum was computed by doubling the N fertilizer/corn price ratio, i.e.:

$$\frac{\text{Price of N fertilizer } (P_n)}{\text{Price of corn } (P_y)} \times 2$$

and equating to the marginal product as mentioned before. A ratio of 4:1 for price of N fertilizer to price of corn was used. Although the 4:1 ratio was selected to illustrate only the procedure, it is assumed to be representative for the actual price per kg of N fertilizer and corn in the area of study.

In order to estimate the optimum N rate for corn that maximizes returns according to the economic criterion selected, over a long term, a weighting procedure which makes use of probabilities was employed. This procedure consisted of simulating the optimum N rate for different levels of rainfall, using the yield equation. Then, each optimum nitrogen rate was multiplied by its respective rainfall probability level and the products were added. The resulting value was the optimum N fertilizer rate. Using this procedure, optimum N rates for several locations in the area of study were determined.

Finally, using weather records, corn-yield simulations were made for different rooting depths and several locations in the area of study. In doing this corn-yield simulation, the optimum N rate and average values for other variables included in the yield-predicting model were used.

IV. RESULTS AND DISCUSSION

A. Light-textured soils

1. Evaluation of weather approaches

In order to characterize the weather-yield relationship in the light-textured soils, the following approaches were used: a moisture stress index, rainfall during critical phenological periods, and a wilting plant index based on visual symptoms of plant wilting. Correlation and regression techniques were used to evaluate these weather approaches.

As mentioned earlier, several moisture-stress indexes were developed in this research. Table 9 shows the correlation coefficients between yield and these stress indexes. This table also shows the correlation between moisture-stress indexes. Correlation coefficients between yield and stress indexes ranged from -0.320 for MS1 to -0.378 for MS7. All correlation coefficients were significant at the 1% level. The correlations between stress indexes were high, ranging from .752 to .999. This indicates that there was some difference in the approaches used to estimate available soil moisture. Including an adjustment for evaporation decreased the correlation coefficient.

The final test to select only one of the moisture-stress indexes for comparison with other weather approaches and for further modeling was made by a series of regressions. A

Table 9. Simple correlation coefficients between yield and moisture stress indexes[a] (MSI) and between moisture stress indexes for light-textured soils (n=80)

Vari-able	Moisture stress indexes						
	MS1	MS2	MS4	MS5	MS5A[b]	MS7	MS7A[b]
YIELD	-.320	-.340	-.367	-.363	-.357	-.378	-.367
MS1	-	.952	.887	.835	.840	.788	.819
MS2		-	.915	.897	.901	.804	.834
MS4			-	.835	.843	.951	.974
MS5				-	.999	.752	.768
MS5A					-	.760	.778
MS7						-	.985
MS7A							-

[a]Moisture stress indexes are numbered according to the approach used to estimate available soil moisture (see Table 2).

[b]Evaporation rate was modified from 0.10" to 0.15" for the top 6" in the soil moisture program.

regression model, where yield was expressed as a function of applied nitrogen fertilizer, was used as the base model. Each stress index was added, one at a time. The regressions were evaluated by the improvement in the R^2 above that of the base model. The results of this test are presented in Table 10. According to the R^2 value, the best stress index was MS7 in which the R^2 was 14.2% above that of the base model. This stress index was selected for comparison with other weather

Table 10. R^2 improvement due to addition of moisture-stress indexes to the base yield regression model for light-textured soils (n=80)

Moisture stress index[a]	R^2	Improvement in R^2
Base model (Yield = N + N^2)	.289	-
MS1	.390	.101
MS2	.404	.115
MS4	.423	.134
MS5	.421	.132
MS5A	.417	.128
MS7	.431	.142
MS7A	.422	.133

[a]See explanation of moisture-stress indexes in Table 2.

approaches and for further modeling.

Rainfall during critical phenological periods was another approach used to characterize the weather-yield relationship. Table 11 shows the correlation coefficients between yield and several rainfall periods surrounding the silking date. It can be observed that total rainfall for 55 days before silking and 25 days after silking date had the highest correlation coefficient (0.461). These results are in close agreement with those found by other researchers. Dale (1948) found that total rainfall comprising six weeks before silking and three weeks after silking date explained more corn-

Table 11. Simple correlation coefficients between yield and several rainfall periods around silking date for light-textured soils (n=80)

Critical period			
Before silk	After silk	Total	
----------------(days)----------------			r
40	15	55	0.377**
45	20	65	0.375**
50	20	70	0.406**
50	25	75	0.407**
55	15	70	0.440**
55	20	75	0.453**
55	25	80	0.461**
60	20	80	0.442**
60	25	85	0.454**

**Significant at the 1% level.

yield variation in Iowa counties. Ortiz-Solorio (1974) found that rainfall occurring 50 days before silking and 30 days after silking had the highest correlation with corn yields.

The evaluation for the three weather approaches selected in this research is presented in Tables 12 and 13. In these tables, MS7 represents the stress index. R80 represents total rainfall for an 80-day critical period surrounding silking date. WPI is the wilting plant index, which included the number of days where symptoms of plant wilting

Table 12. Simple correlation coefficients between yield and several approaches used to characterize weather for light-textured soils (n=80)

	MS7	R80	WPI
YIELD	-.378	.461	-.537
MS7		-.715	.768
R80		-	-.832
WPI			-

Table 13. R^2 improvement due to addition of weather characterization approaches to the base yield regression model

Moisture stress approach		Improvement in R^2
Base model (Yield = N + N^2)	.289	
MS7	.431	.142
R80	.500	.211
WPI	.616	.327

were observed. This index comprised a 70-day period, 39 days before silking and 30 days after silking. Table 12 presents the correlation coefficients between yield and weather approaches. All correlation coefficients were significant at the 1% level. These coefficients ranged from -0.378 for MS7 to -0.537 for WPI. It is interesting to note the high correlation among the weather approaches used, especially that between R80 and WPI which reached a value of -0.832. Weather approaches were also evaluated according to the R^2 improvement to a base regression model, as explained before. The results of this test are presented in Table 13. This table shows that WPI had the highest R^2 (0.616) which was 32.7% above that of the base model. Thus, according to this test, the best weather approach was WPI, followed by R80, and then MS7. Single values for these three weather approaches are given in Appendix Table A4.

There are several reasons that could explain the low performance of the moisture-stress index MS7 as compared with the other weather approaches used. It is clear that the modifications made to adapt the soil-moisture program to the area of study in Mexico were not sufficient. This means that in order to obtain a good weather characterization using this approach, major modifications in the soil-moisture simulation model have to be made. Among the possible modifications, those of special importance are the following: (1) the rate of transpiration, which is a function of soil type and atmospheric demand; (2) the potential evapotranspiration/pan evaporation ratio through the growing season; and (3) the rooting extraction schedule, which is a function of rooting development of the crop and available moisture in the soil profile. Thus, it is necessary to carry out local research in order to develop these basic relationships to modify the soil moisture simulation model.

The relatively good performance for R80 and WPI, as compared with MS7, can be explained in part by the low rainfall conditions present in the light-textured soils area. Under these conditions, a single meteorological variable (rainfall in this case), or a simple visual method to monitor wilting plants, could be used to characterize the weather-yield relationship adequately. This is because available moisture is the most limiting factor to corn yields in that area.

2. Corn-yield-predicting models

a. Development As mentioned earlier, three yield regression models were developed, one for each weather approach. In addition to the weather factor, the applied nitrogen fertilizer, as well as soil and environmental variables, were included in developing these models. Final corn-yield models with weather approaches MS7, R80, and WPI, and other variables are presented in Tables 14, 15 and 16, respectively. These tables show the selected variables, estimates (regression coefficients) for these variables, as well as the interpretation of the effect of the variable on yield.

Since the independent variables were coded by subtracting their minimum value, estimates for the intercept and for the variables are expressed as their lowest observed value. Signs for the estimates of the selected variables in each yield model were as expected. That is, all were consistent with scientific knowledge. However, magnitude of these estimates, for a given variable, may change depending on local conditions. All selected variables for the three models were significant at least at the 5% level, with the exception of the variable R80 in Table 15. This variable was kept in the model because the interaction N*R80 was significant at the 5% level.

The R^2 for these models ranged from 0.58 for model 1, where MS7 was included, to 0.74 for model 3, where WPI was included, in addition to other variables. Since corn-yield models were developed mainly to predict corn yields using independent data, only those variables well represented in the region of interest were considered. An agronomic criterion was used in making this *a priori* selection. Laird and Cady (1969) found that using an agronomic approach to obtain

Table 14. Corn-yield-prediction model 1 with MS7 as an alternative approach to estimate the effect of moisture stress (MS7) and other variables on corn yields[a]

Variable	Estimate	Interpretation of the effect of the variable on yield
INTERCEPT	1003.82	
N	37.965**	Maximum yield occurred at N=113.7 kg/ha (at average soil nitrogen conditions)
N^2	-0.133*	
MS7	-85.140**	Yield decreased at a decreasing rate as moisture-stress index changed from zero to 39.5
$MS7^2$	1.768*	
SN	25.005**	Yield increased 25 kg/ha per unit of total soil nitrogen (at N = 0)
N*SN	-0.209*	As total soil nitrogen increased, corn yield response to applied N decreased
PAWC7	6.702**	Yield increased 6.7 kg/ha per mm of PAWC at rooting depth

[a] R^2 = 0.58; error mean square = 722,476; error d.f. = 72.

**,*Significant at the 1% and 5% levels, respectively.

Table 15. Corn-yield-prediction model 2 with R80 as an alternative approach to estimate the effect of rainfall (R80) and other variables on corn yields[a]

Variable	Estimate	Interpretation of the effect of the variables on yield
INTERCEPT	978.08	
N	30.509**	Maximum yield occurred at N=109.0 kg/ha (at average soil nitrogen and average rainfall conditions)
N^2	-0.143**	
R80	1.881⁺	Yield increased 1.9 kg/ha per mm of rainfall (at N = 0)
N*R80	0.041*	As rainfall increased, corn yield response to applied N increased
SN	22.643**	Yield increased 22.6 kg/ha per unit of total soil nitrogen (at N = 0)
N*SN	-0.245**	As total soil nitrogen increased, corn yield response to applied N decreased
SILK	-97.809**	Yield decreased 97.8 kg/ha as silking date was delayed after August 26 (earliest date)
PAWC7	8.374**	Yield increased 8.4 kg/ha per mm of PAWC at rooting depth

[a]R^2 = 0.70; error mean square = 524,543; error d.f. = 71.

**,*,⁺Significant at the 1%, 5%, and 14% levels, respectively.

Table 16. Corn-yield-prediction model 3 with WPI as an alternative approach to estimate the effect of wilting plant index (WPI) and other variables on corn yield

Variable	Estimate	Interpretation of the effect of variables on yield
INTERCEPT	819.24	
N	46.788**	Maximum yield occurred at N=111.2 kg/ha (at average soil nitrogen and average WPI conditions)
N^2	-0.140**	
WPI	-23.973*	Yield decreased 24 kg/ha per unit of wilting plant index (at N = 0)
N*WPI	-0.501**	As WPI increased, corn yield response to applied N decreased
SN	23.741**	Yield increased 23.7 kg/ha per unit of soil nitrogen (at N = 0)
N*SN	-0.267**	As soil nitrogen increased, corn yield response to applied N decreased
PAWC7	15.236**	Yield increased at a decreasing rate as PAWC7 changed from 63 to 250 mm of water at rooting depth
$PAWC7^2$	-0.061*	

[a]R^2 = 0.74; error mean square = 460,024; error d.f. = 71.

**,*Significant at the 1% and 5% levels, respectively.

a yield-predicting model will invariably lead to a model with the minimum number of variables. This is because only those variables that account for variation in yield will be included in the model. Models built based on statistical criteria only may include unimportant variables due to the correlation problem. Consequently, the R^2 value of a "statistical model" may be higher than that of an "agronomic-statistical model", as employed in this study. However, the capability for yield predictions using independent data is better in the latter type of models, as demonstrated by Laird and Cady (1969).

In this study, the regression models presented in Tables 14, 15 and 16 contain 4, 5, and 4 initial variables, respectively. In addition to applied nitrogen fertilizer and the corresponding weather factor, all models included soil nitrogen (SN) and available soil moisture in rooting depth (PAWC7). Only model 2 in Table 15 included the variable days from planting to silking date (SILK). This characteristic may have some practical importance as the number of variables is kept to a minimum, making it easier to use a yield-predicting model in the area of study.

b. Evaluation Corn-yield-predicting models were evaluated using independent yield data. As mentioned before, 16 observations from four experimental sites were used for this test. These observations were omitted from the original data used in developing yield-prediction models.

Table 17 shows this evaluation. Here the differences between estimated yields by each of the three models and actual yields were used to compute the various indicators of yield reliability. Bias varied from -183 kg/ha for model 2 where R80 was included, to -450 kg/ha for model 1 where MS7 was included. A negative bias indicates that corn yields tend to be underestimated by these models, whereas a positive bias would indicate the opposite. It is desirable to develop models with bias close to zero. Bias expressed on a percentage basis (relative bias) ranged from -5.4% to -13.4% for the three yield-predicting models.

The accuracy in predicting corn yields evaluated by the standard deviation ranged from 374 kg/ha for model 3, where WPI was included, to 621 kg/ha for model 1, where MS7 was included. In other words, average predicting errors using the best yield model would be of 374 kg/ha (5.8 bu/A). Relative standard deviation for these models ranged from 12% to 21.3%. Looking at Table 17, it can be observed that all models performed poorly in experimental site 409. The low accuracy in this site increased the predicting error for these models.

Table 17 also shows the correlation coefficients between predicted and actual yields. These coefficients ranged from 0.85 for model 1 to 0.93 for model 3.

Figures 8, 9 and 10 show the relationships between actual

Table 17. Evaluation of corn-yield-prediction models using 16 observations omitted from original data used in developing yield-prediction models

Exptl. site	N kg/ha	Actual yield (kg/ha)	Model 1 $\hat{Y}_1-Y$	Model 2 $\hat{Y}_2-Y$	Model 3 $\hat{Y}_3-Y$[a]
303	0	1880	169	442	137
303	40	2830	54	337	-9
303	80	2790	495	756	378
303	120	3510	-257	-51	-452
409	0	2750	-1435	-772	-805
409	40	3740	-1361	-764	-798
409	80	4090	-1074	-574	-599
409	120	4100	-871	-501	-508
412	0	1030	-593	-20	-120
412	40	2630	-887	-280	-292
412	80	3700	-1077	-466	-383
412	120	3750	-672	-91	98
504	0	3590	-105	-401	-612
504	40	4310	46	-238	-239
504	80	4470	297	-11	210
504	120	4650	67	-298	154
Bias (kg/ha)			-450	-183	-240
Relative bias (%)			-13.4	-5.4	-7.1
Standard deviation (kg/ha)			621	426	374
Relative std. dev. (%)			21.3	13.4	12.0
Correlation between $\hat{Y}_i$ and yield (Y)			0.85	0.90	0.93

[a]Corn yield differences between estimated yield ($\hat{Y}_i$) for corn-yield-predicting models 1, 2 and 3, and actual yield (Y).

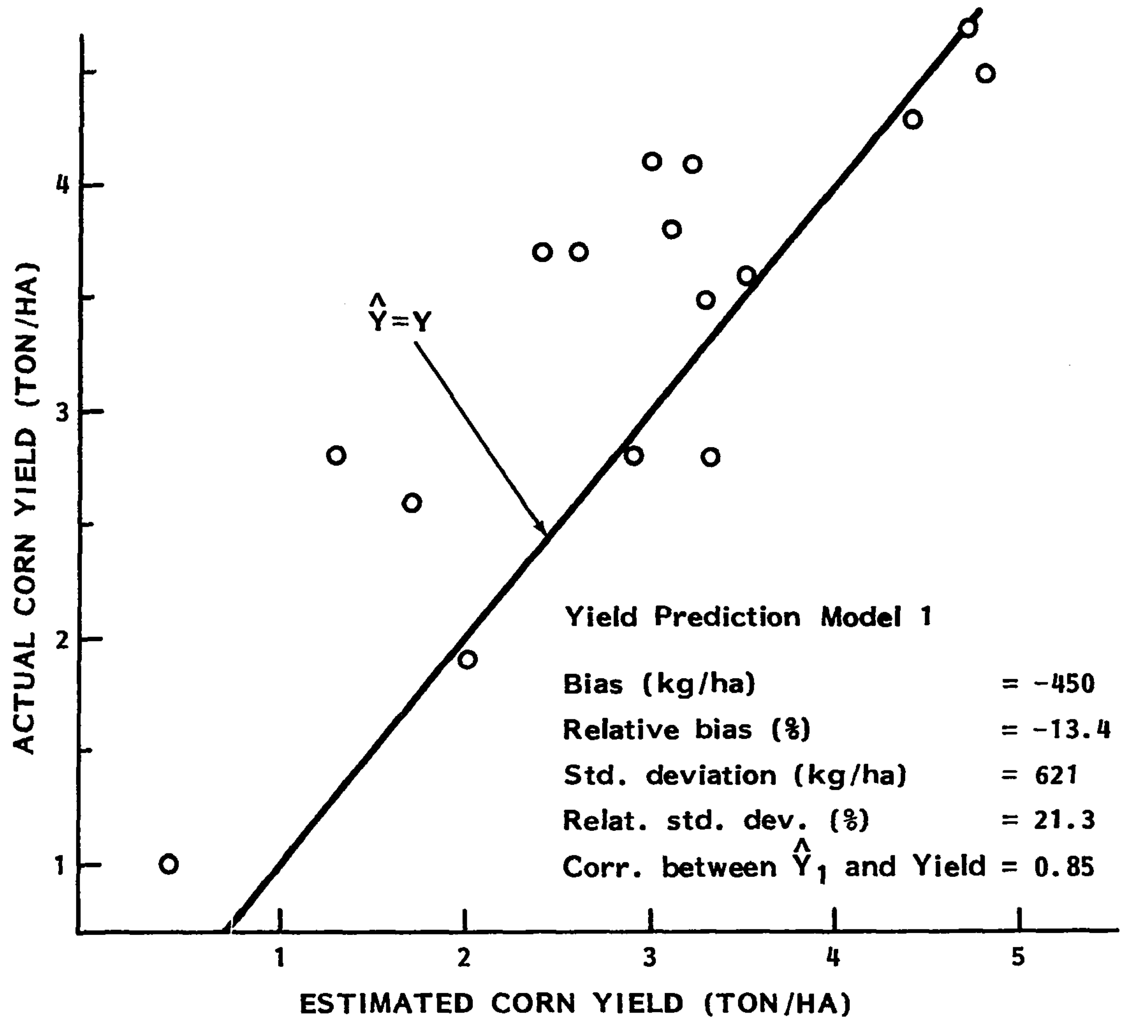

Figure 8. Actual corn yield vs estimated corn yield with moisture-stress index (MS7) included in the yield prediction model for light-textured soils

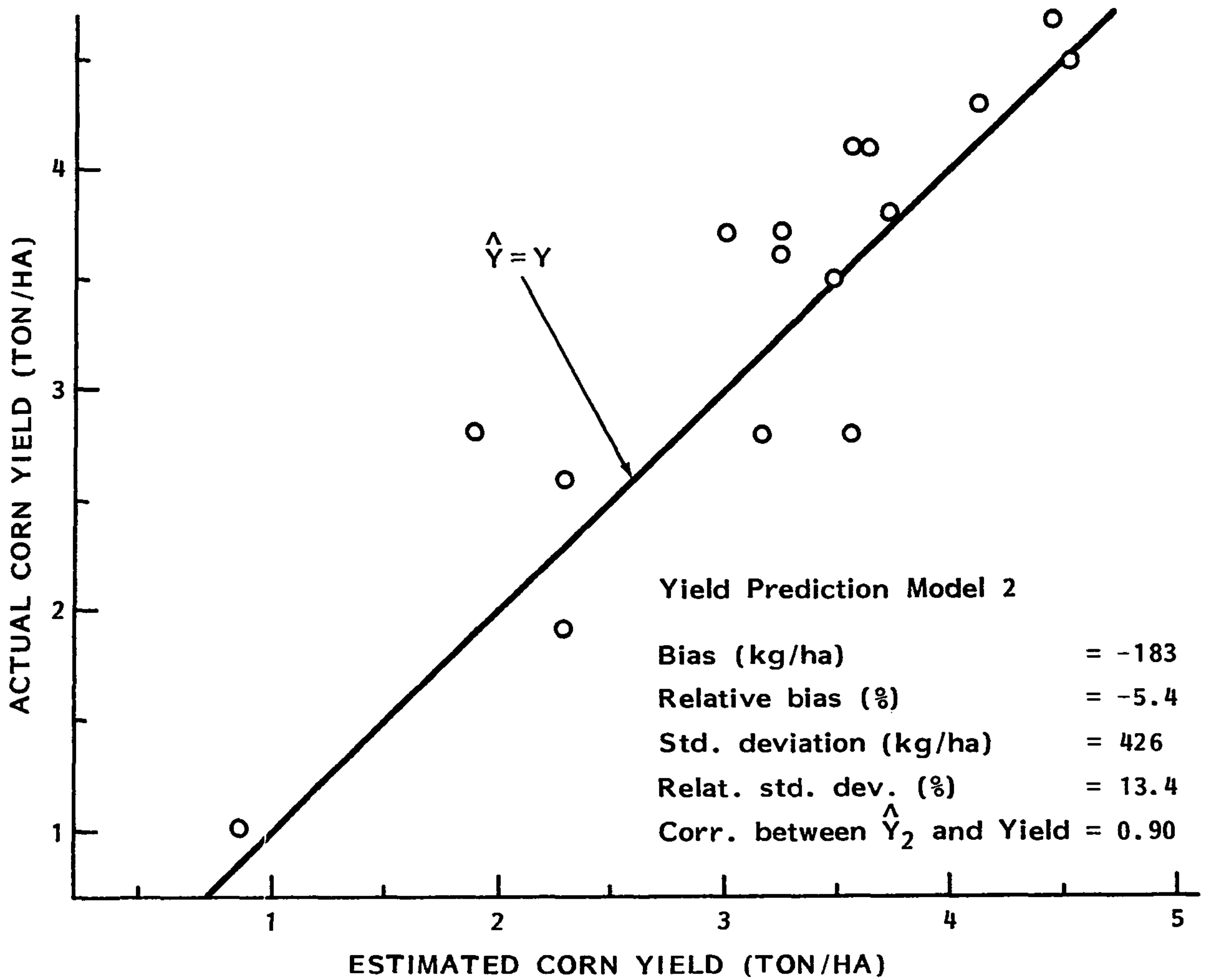

Figure 9. Actual corn yield vs estimated corn yield with rainfall (R80) included in the yield prediction model for light-textured soils

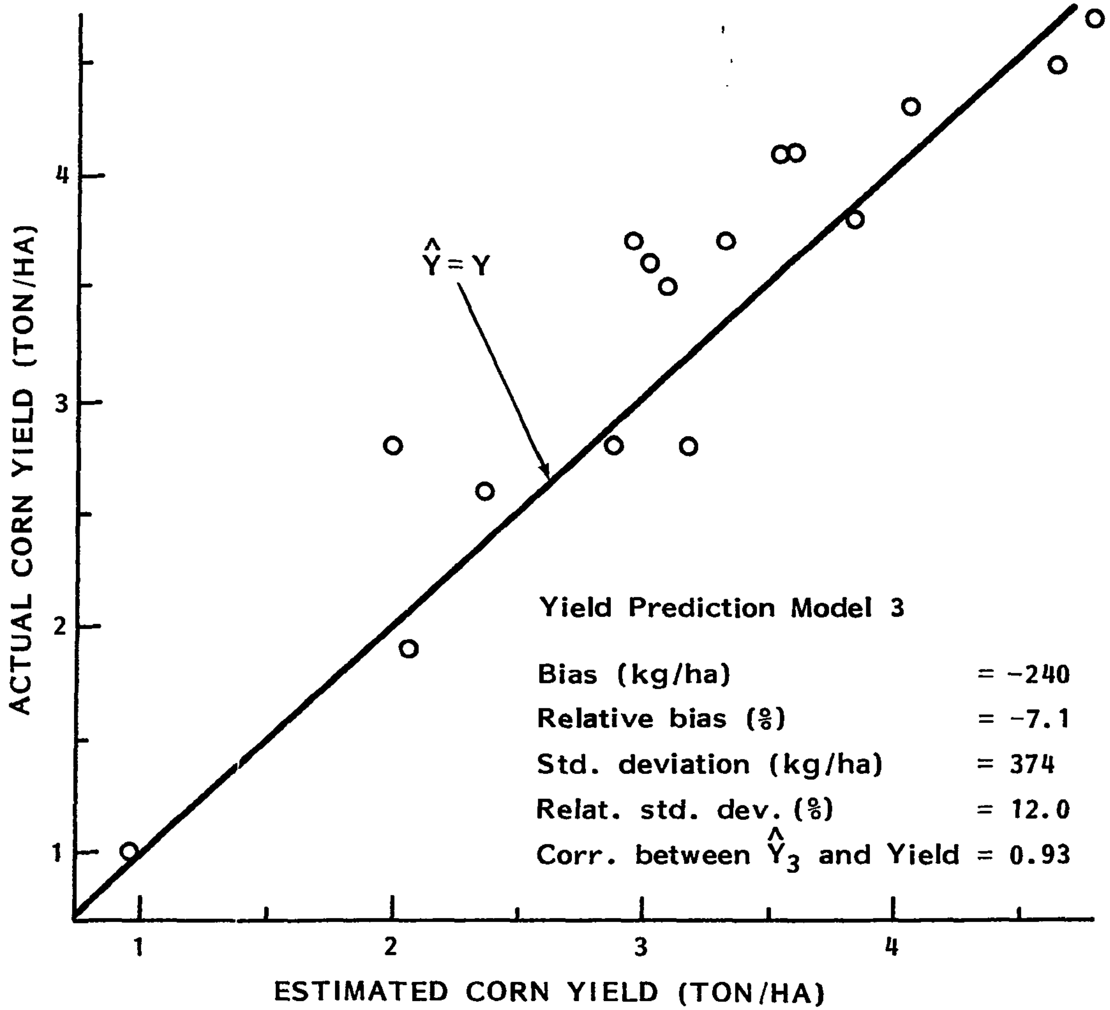

Figure 10. Actual corn yield vs estimated corn yield with wilting plant index (WPI) included in the yield prediction model for light-textured soils

vs predicted corn yields for corn-yield-predicting models 1, 2 and 3, respectively. These plots also serve to illustrate the evaluating criteria discussed above. For instance, all plots show more points above the 1:1 line, which indicates the tendency of the three models to underestimate corn yields.

Based on the criteria used to evaluate yield-predicting models, new yield predictions using another independent yield data set are expected to be more accurate if model 3 is used. It should be noted, however, that in evaluating these models only 16 observations were used (about 17% of original data). It would have been very desirable to have used more observations for this test. However, it was not possible because of the limited amount of available yield data.

Corn-yield differences between predicted and actual yields were further evaluated using a variance component method. This test was made because yield observations used came from four fertilizer treatments tested in each experimental site. Table 18 shows the variance components of these yield differences for three yield models. In order to facilitate the discussion of this evaluation, the variance components expressed on a percentage basis will be used. The "between sites" variance component accounted for 87.1%, 77.0% and 45.7% of the yield differences between predicted and actual yields for models 1, 2 and 3, respectively. The "within

Table 18. Variance components of the differences between actual yield (Y) and predicted yield ($\hat{Y}_i$) for three yield models developed for the light-textured soils area

Variance source	d.f.	Expected mean squares: Sum of squares	Mean squares	Variance component	%
		Model 1 (DIFF Y - $\hat{Y}_1$)			
Total	15	5,777	385	466	100.00
Between sites	3	3,057	1,686	406	87.14
Within sites (Error)	12	720	60	60	12.86
		Model 2 (DIFF Y - $\hat{Y}_2$)			
Total	15	2,718	214	214	100.00
Between sites	3	2,127	709	165	77.00
Within sites (Error)	12	591	49	49	23.00
		Model 3 (DIFF Y - $\hat{Y}_3$)			
Total	15	2,103	140	154	100.00
Between sites	3	1,097	366	70	45.67
Within sites (Error)	12	1,006	84	84	54.33

sites" variance component, that is, that among fertilizer treatments, accounted for 12.1%, 23.0% and 54.3% for models 1, 2 and 3, respectively. The variance component between sites plus that within sites equals 100.0%.

A large "between sites" variance component means that a predicting model detects mostly changes in yield caused by site differences, and it is less sensitive to detect yield changes within sites (yield differences caused by N levels employed in each experimental site). As the "within sites" variance component increases, accuracy in yield predictions tends to be improved. This can be checked by comparing the standard deviation of yield differences given in Table 17 for models 1, 2 and 3, with the "within sites" variance component values for the same yield models presented in Table 18. Ideally, a good yield predicting model should detect yield variation both between sites and within sites in about the same proportion. Model 3 which accounted for 45.7% and 54.3% of yield variance between sites and within sites, respectively, is a good example to illustrate this concept.

3. Determination of optimum N rates using simulation techniques

Recommended fertilizer rates are usually obtained from an average fertilizer response curve; for example, from 5 years of data at a certain location. If rainfall was less than normal during those 5 years, the recommended rate would be less than average, or if rainfall was greater than normal, the recommended rate would be greater than average. Because the amount of rainfall influences fertilizer response curves between years for any specific location, the definition of yield as a function of both applied N fertilizer and rainfall has special utility. Simulation techniques make it possible to estimate the expected fertilizer response under a wide range of weather conditions, using long-term weather records, which otherwise would take many years of field work.

In order to simulate the fertilizer response using historic weather records, corn-yield-predicting model 2 was used. This model included rainfall (R80) as the variable to characterize weather. Model 2 was used because long-term rainfall records were available, on one hand, and because there was little difference in corn yield predictions between this model and model 3 (see Table 17). The standard deviation of corn-yield differences were 426 kg/ha and 374 kg/ha for models 2 and 3, respectively. Another reason why model 2 was employed is the high correlation found between R80 and WPI ($r = -0.83$). Figure 11 shows the relationship between R80 and WPI. No attempt was made to transform mm of rainfall to a wilting plant index (WPI) using the equation developed to establish this relationship (see Figure 11).

Model 2 first was reestimated using all available data (four experimental sites omitted for models evaluation were

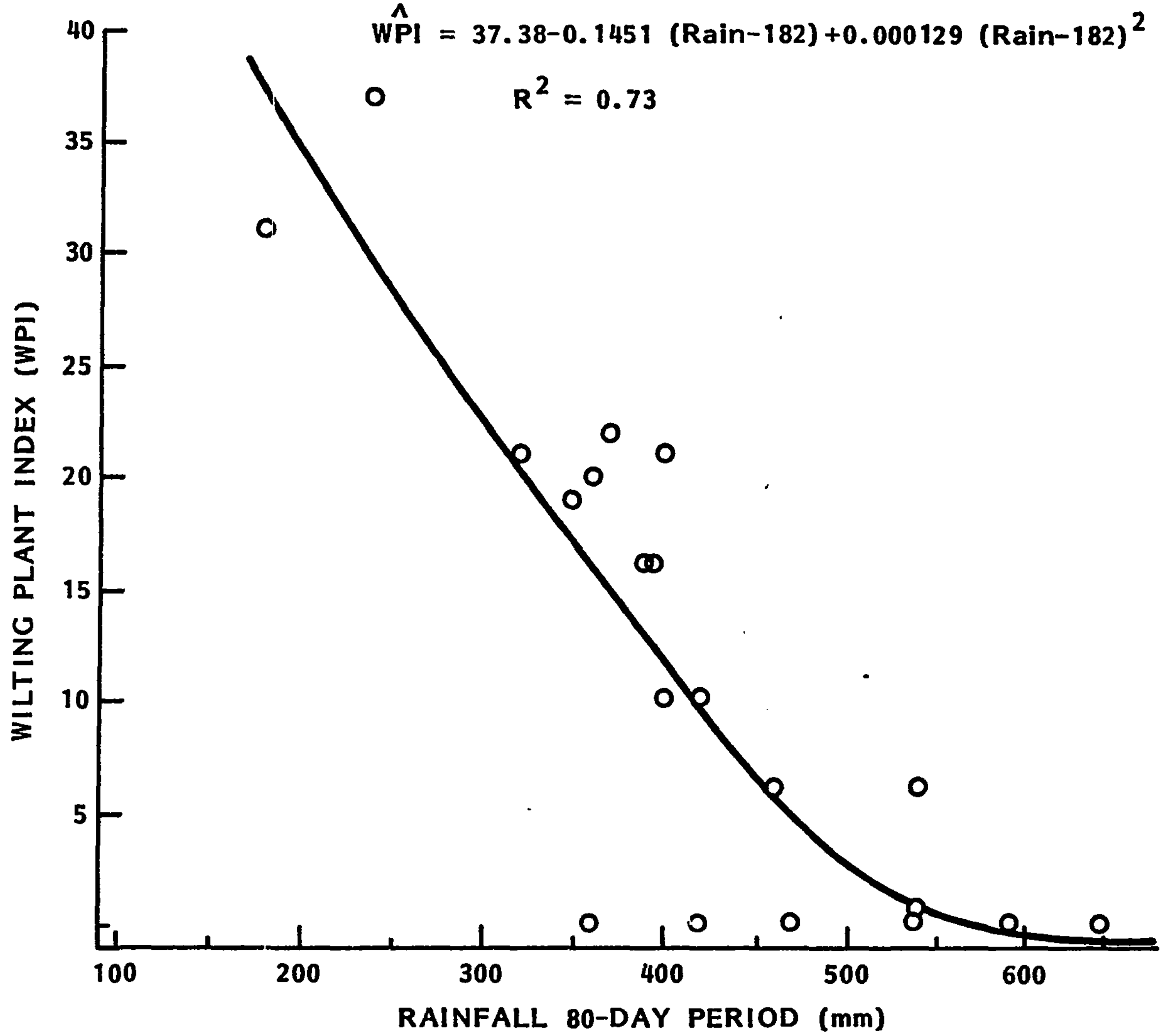

Figure 11. Relationship between wilting plant index and rainfall for the 80-day critical period around silking date for light-textured soils area

included to give 24 experimental sites in total). The re-estimated yield model is presented in Table 19. The R^2 of the reestimated model increased 1% and the error mean square decreased because more degrees of freedom were available. Signs for the estimates of the variables remained the same, and the magnitude of these estimates were similar in both models.

Using the reestimated yield model of Table 19, all variables included except N and R80 were replaced by their average values. This was done in order to express the model in terms of N fertilizer and rainfall only. The reduced form for this model was the following:

$$\text{Yield} = 1731.63 + 20.765\ N - 0.138\ N^2 + 1.630\ R80 + 0.042\ N*R80 \quad .$$

The next step consisted of replacing the total amount of rainfall recorded during the 80-day critical period (R80) using a 31-year period of rainfall records. The yield equation presented above was then used to obtain optimum N rates for the limited capital conditions earlier described, taking the first derivative of yield with respect to N and equating this to the inverse price 2*ratio. Optimum N rates were computed for four locations using historic weather records of four weather stations in the area of study.

Relative frequency diagrams of optimum N rates for four locations are given in Figure 12. Individual values of optimum N rates for these locations are presented in Appendix

Table 19. Reestimated final yield prediction model (including all experimental sites) to estimate the effect of rainfall (R80) and other variables on corn yields[a]

Variable	Estimate	Interpretation of the effect of the variables on yield
INTERCEPT	1077.86	
N	29.793**	Maximum yield occurred at N=111.3 kg/ha (at average rainfall and average total soil nitrogen conditions)
N^2	-0.138**	
R80	1.630+	Yield increased 1.6 kg/ha per mm of rainfall (at N=0)
N*R80	0.042**	As rainfall increased corn yield response to applied N increased
SN	20.620**	Yield increased 21 kg/ha per unit of total soil nitrogen (at N=0)
N*SN	-0.244**	As total soil nitrogen increased corn yield response to applied N decreased
SILK	-98.615**	Yield decreased 99 kg/ha as silking date was delayed after August 26 (earliest date)
PAWC7	9.441**	Yield increased 9.4 kg/ha per mm of PAWC at rooting depth

[a] R^2 = 0.71; error mean square = 460,144; error d.f. = 87.

**,*,+Significant at the 1%, 5%, and 17% levels, respectively.

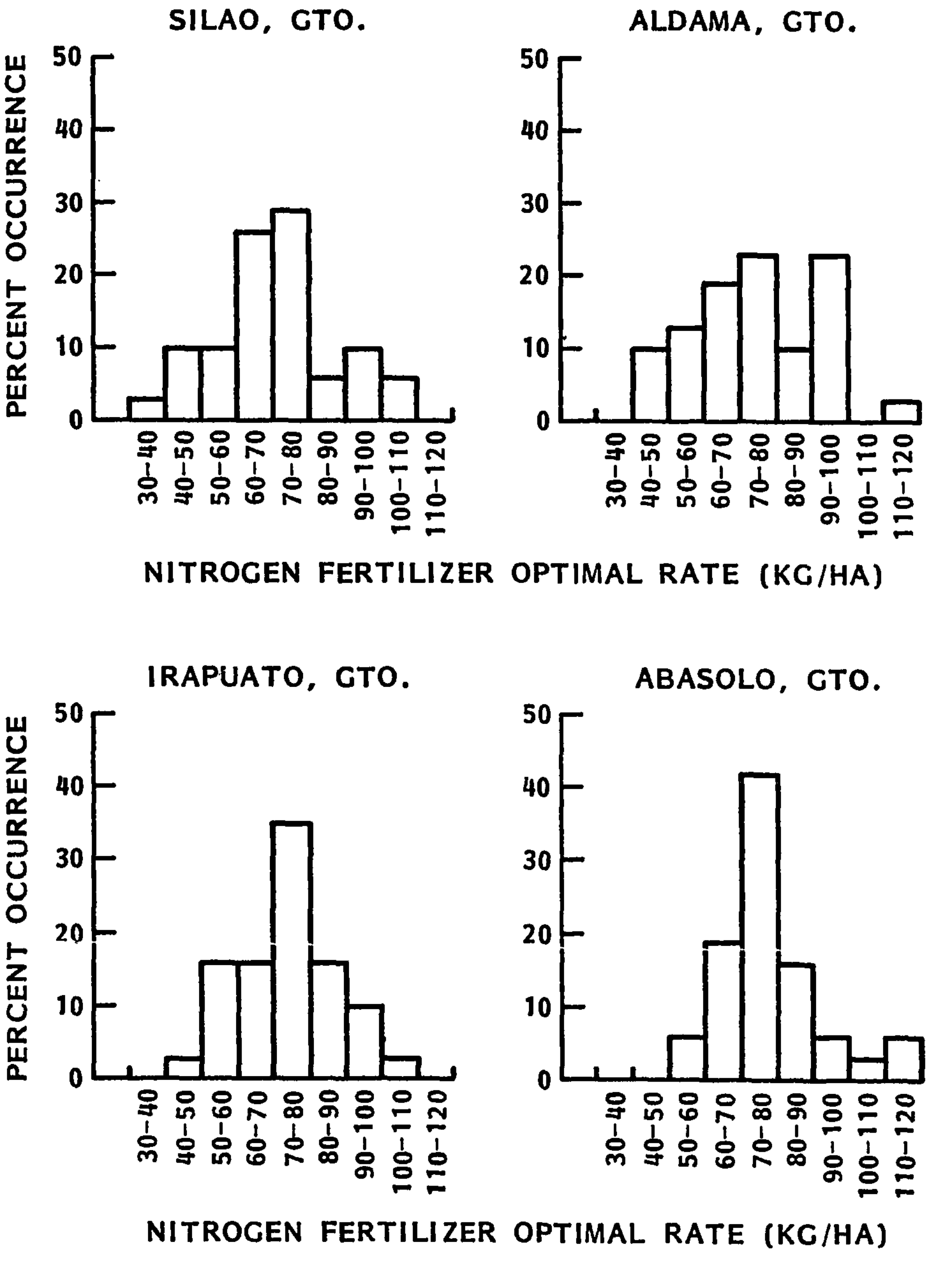

Figure 12. Relative frequency diagrams of nitrogen fertilizer optimal rates for a 31-year period for four locations in the area of study

Table A5. Looking at Figure 12, it can be observed that there was a great deal of year-to-year variability in N fertilizer optimal rates, caused by rainfall fluctuation. Optimal rates of N in these four locations ranged from 33 kg/ ha for the driest 80-day critical period to 118 kg/ha for the wettest one, using a 31-year period of rainfall records. The standard deviation of N optimal rate in these locations varied from 14.3 kg/ha for Abasolo, where rainfall is relatively high and less variable, to 17.9 kg/ha for Aldama, where rainfall is lower and more variable. This can be observed by looking at the individual plots for these two locations given in Figure 12. Here, simulated N optimal rates for Aldama show more divergence than those for Abasolo.

Since the response of corn to applied N under these conditions was quite variable between years, a procedure to estimate N optimal rates, which accounts for weather variability, was used. As mentioned earlier, a weighted procedure which makes use of rainfall probabilities was used. This procedure consisted first of simulating yield responses to applied N for six levels of rainfall using the final yield prediction model. These corn yield curves, presented in Figure 13, clearly show that the optimum N rate is strongly affected by the amount of rainfall received during the 80-day critical period surrounding silking. Figure 13 also shows that, in years of low rainfall, corn yields are

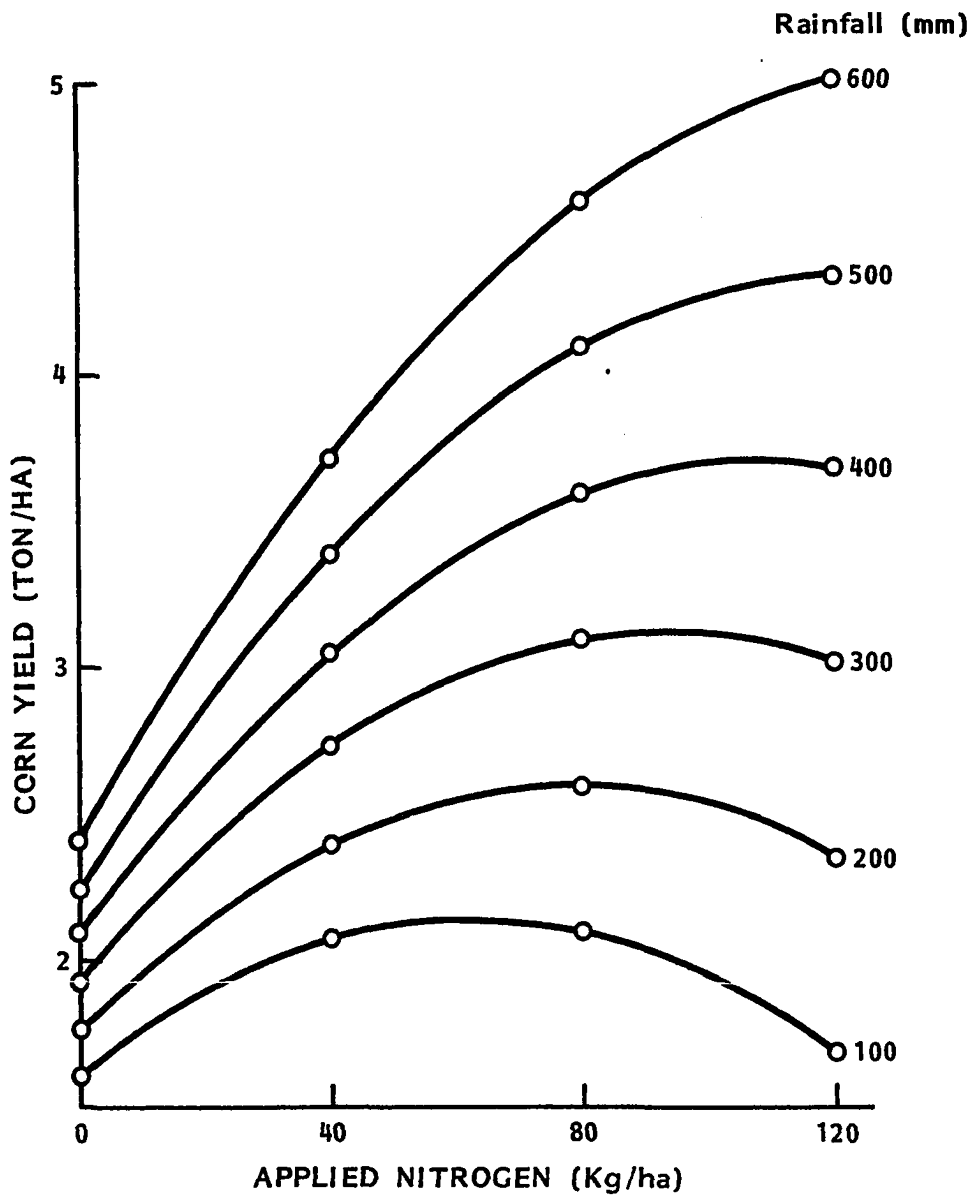

Figure 13. Corn yield curves estimated from the yield prediction model 2 for six levels of rainfall (mm), during the 80-day critical period with average levels of the other site variables

maximum at considerably lower rates of applied N than in years with adequate rainfall. The next step was to compute the optimal rate of N for each of these rainfall levels, according to an economic criteria described earlier. These optimal rates of N are given in Table 20. Then each optimal nitrogen rate was multiplied by its respective rainfall probability (Table 21). For instance, the optimum N rate for Silao was computed as follows:

$$\text{Opt. N rate} = (33.8*0.01)+(48.9*0.11)+(64.2*0.30)+ (79.4*0.30)+(94.6*0.17)+(109.9*0.07) = 73 \text{ kg/ha} .$$

The same weighting procedure to estimate optimum N rates was applied to the other three locations. Table 22 reports these results. It should be noted that the weighting procedure employed here is about equivalent to that used in game theory where the probabilities of occurrence for several levels of rainfall are used to select the optimal rate of N from several alternatives. In both cases, with the use of rainfall probabilities, it is possible to determine the farmer's economic optimum alternative, viewed as a risk situation rather than in an uncertainty context (Avilan-Camejo, 1978). The optimal N rates given in Table 22, then, are those that will maximize the expected returns for a corn fertilization program over a long term.

Nitrogen fertilizer recommendations obtained using

Table 20. Simulation of nitrogen fertilizer optimal levels using six different amounts of rainfall during the 80-day critical period (55 days before silking and 25 days after silking)

Rainfall (mm)	Optimal nitrogen rate (kg/ha)
100	33.8
200	48.9
300	64.2
400	79.4
500	94.6
600	109.9

Table 21. Rainfall probabilities for the 80-day critical period (55 days before silking and 25 days after silking) in four weather stations

		Rainfall probability						
Weather station	Mean[a] (mm)	<100	100-200	200-300	300-400	400-500	500-600	>600
		mm of rain						
Silao	339	0.01	0.11	0.30	0.30	0.17	0.07	0.04
Aldama	372	0.00	0.06	0.39	0.32	0.16	0.05	0.02
Irapuato	362	0.00	0.03	0.26	0.38	0.23	0.08	0.02
Abasolo	394	0.00	0.01	0.14	0.40	0.32	0.11	0.02

[a]Average rainfall for the 80-day critical period around corn silking date.

Table 22. Optimal fertilizer nitrogen levels for four locations in the area of study

Location	Optimal nitrogen rate (kg/ha)
Silao, Gto.	73
Aldama, Gto.	74
Irapuato, Gto.	79
Abasolo, Gto.	84

simulation techniques like those presented here could be made for any soil and climate if several years of data on crop response to N fertilizer or other agronomic practices and the necessary weather data are available.

4. Simulation of corn yields

Corn yields for several locations in the area of study were simulated using the reestimated yield-predicting model presented in Table 19. In this model, the variables SN and SILK were replaced by their average values. Nitrogen was replaced by the optimum level determined for each location (see Table 22). Since rooting depth was quite variable across the area, simulation of corn yields was made using rooting depths of 30, 60 and 90 cm. Available soil moisture for these three rooting depths was computed and replaced, one at a time, in the predicting model. Finally, the rainfall variable (R80) was substituted in the predicting model using historic rainfall records for a 31-year period and corn yields were computed for these locations and rooting depths. In doing this simulation of corn yields, it was assumed the same crop management level was used as when the field experiments were conducted.

Frequency diagrams of corn yield at three rooting depths and four locations are presented in Figures 14, 15, 16 and 17. A distribution of yields constructed from the simulation results can be a useful tool in decision making. Several statistical parameters can be determined to help the interpretation and use of these relative frequency diagrams of corn yields. Arkin et al. (1980) suggest the following:

1. The probability a certain yield value might occur,
2. The most likely occurring yield,
3. The greatest and smallest occurring yield,
4. The probabilities that the yield may be greater or smaller than a particular value,
5. The average yield value expected over many years, and
6. The expected year-to-year variability in yields over many years.

Appendix Table 6A shows individual corn yield values as well as some of the statistical parameters mentioned above, at three rooting depths for four locations.

Since corn yields were simulated using a 31-year period

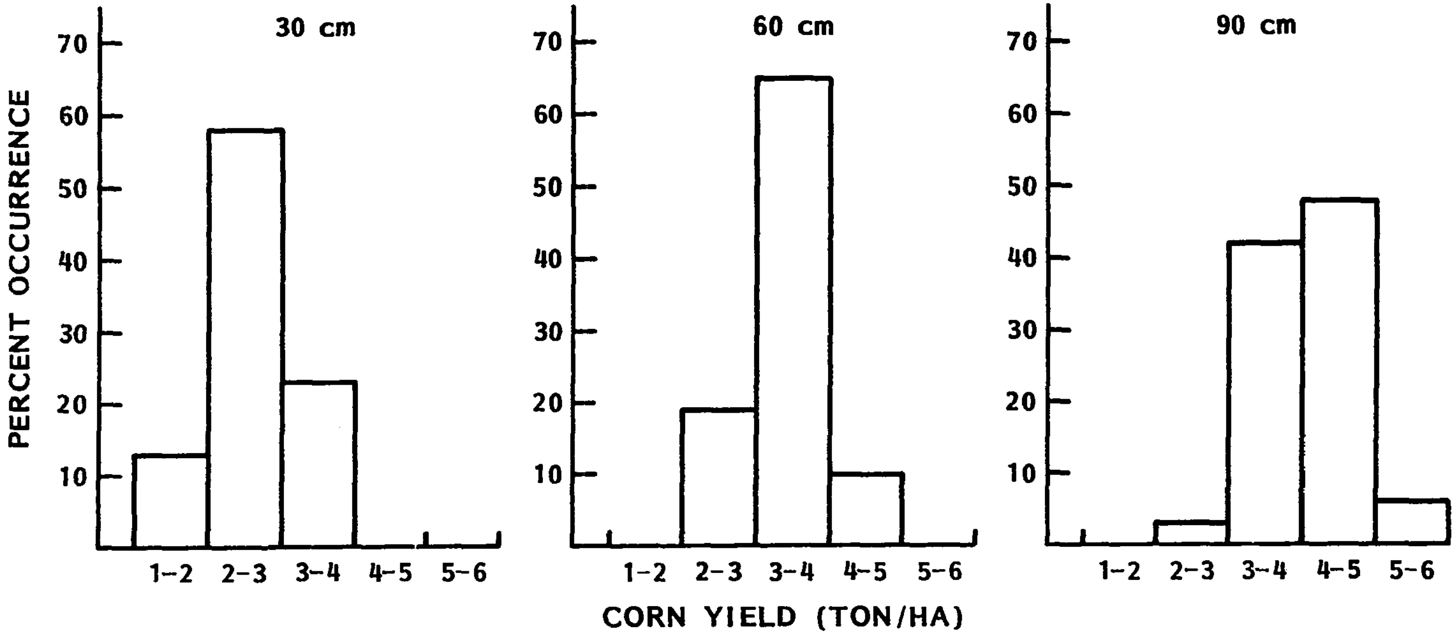

Figure 14. Relative frequency diagrams of corn yield using N optimal rate for three levels of plant-available-water capacity, 72, 144, and 216 mm, at rooting depths of 30, 60 and 90 cm, respectively, for Silao, Gto.

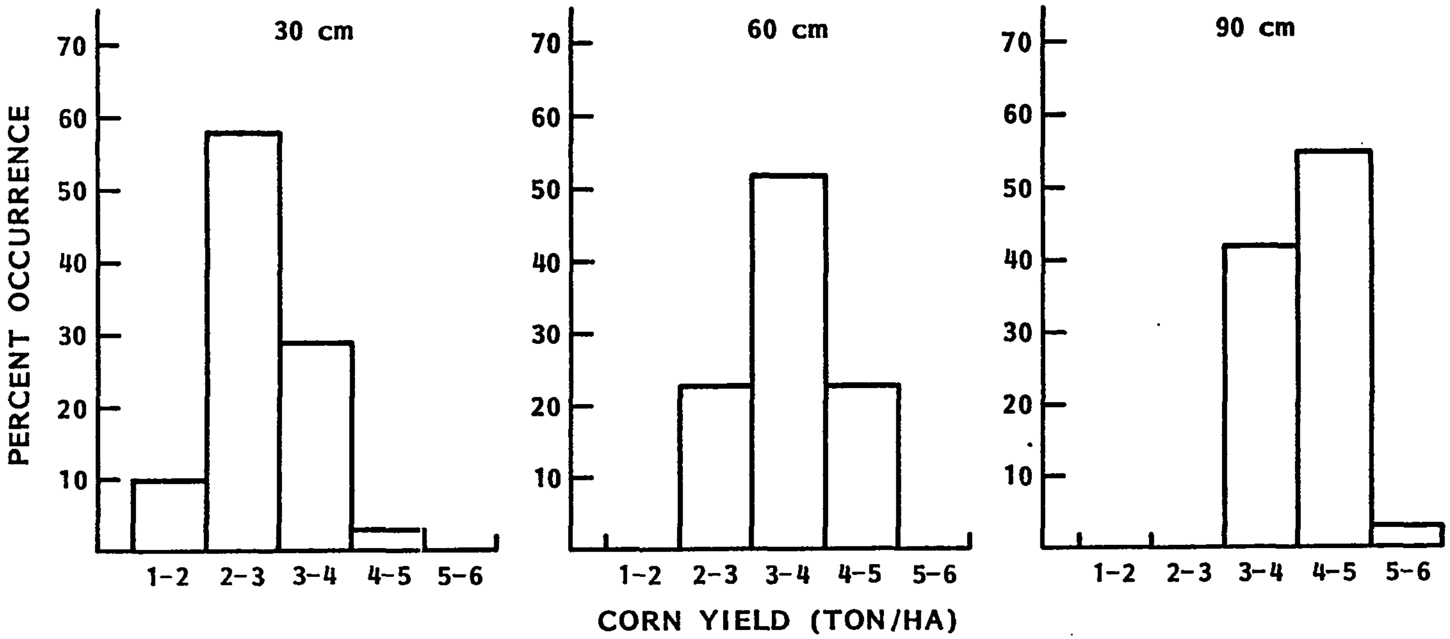

Figure 15. Relative frequency diagrams of corn yield using N optimal rate for three levels of plant-available-water capacity, 72, 144, and 216 mm at rooting depths of 30, 60 and 90 cm, respectively, for Aldama, Gto.

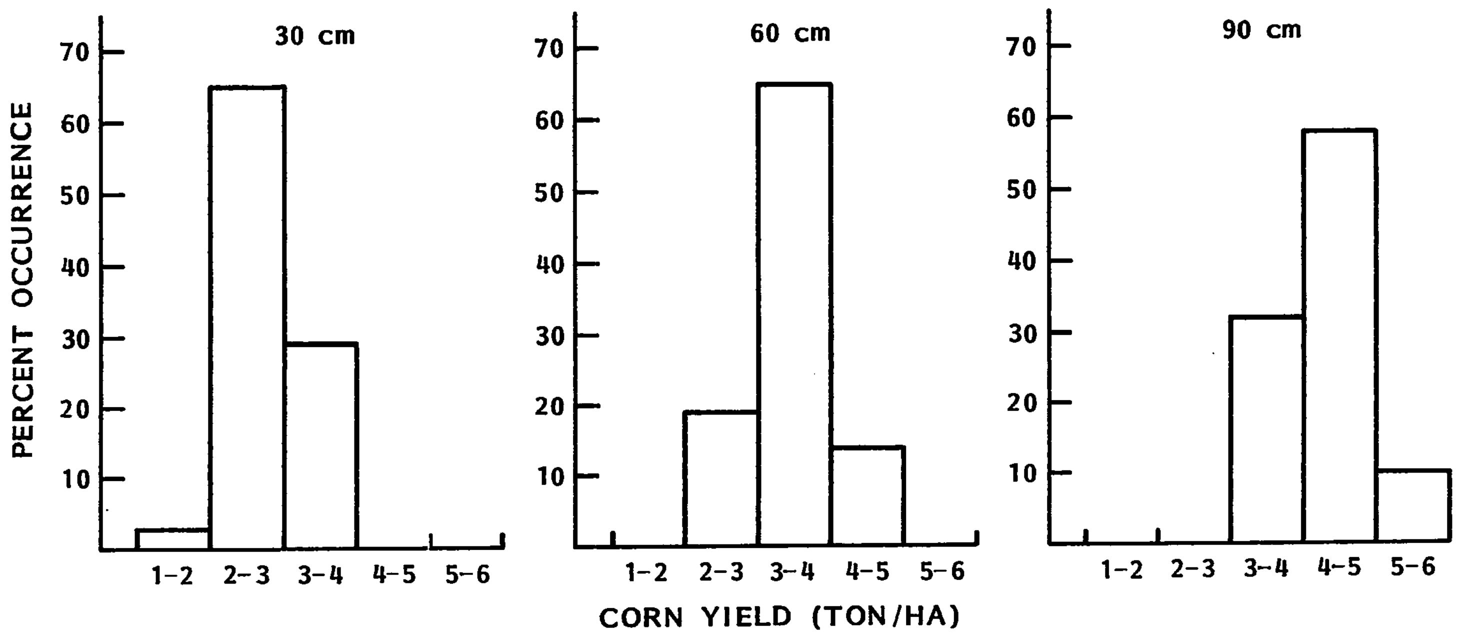

Figure 16. Relative frequency diagrams of corn yield using N optimal rate for three levels of plant-available-water capacity, 72, 144, and 216 mm at rooting depths of 30, 60 and 90 cm, respectively, for Irapuato, Gto.

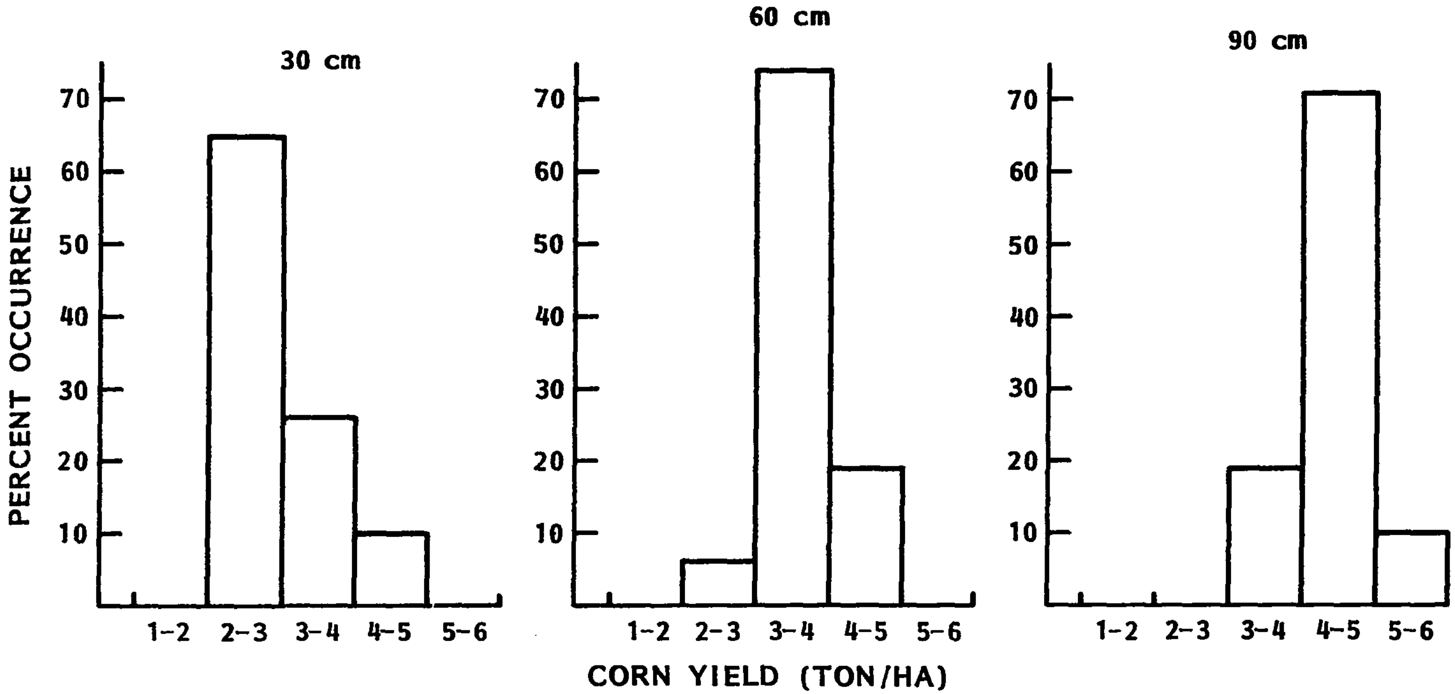

Figure 17. Relative frequency diagrams of corn yield using N optimal rate for three levels of plant-available-water capacity, 72, 144, and 216 mm at rooting depths of 30, 60 and 90 cm, respectively, for Abasolo, Gto.

of rainfall, in making use of the relative frequency diagrams it was assumed that future rainfall will be distributed similar to that for the past 31 years.

It is obvious in Figures 14 through 17 that increasing the depth of maximum rooting from 30 cm to 90 cm resulted in an increase in corn yields. Typical corn yields at 30, 60 and 90 cm rooting depths ranged from 2 to 3 ton/ha, 3 to 4 ton/ha, and 4 to 5 ton/ha, respectively.

Locations used to simulate corn yields showed little change of corn yield variability. The standard deviation for simulated corn yields ranged from 474 kg/ha for Irapuato, Gto. to 558 kg/ha for Aldama, Gto. The overall standard deviation for simulated corn yields of four locations in the light-textured soils was 514 kg/ha.

Yields were more stable as rooting depth increased. Coefficients of variation (C.V.) taking the average of four locations ranged from 18.3% for 30 cm rooting depth to 12.3% for 90 cm rooting depth. The probability of obtaining corn yields above 2 ton/ha, taking the average of four locations, was 93.5, 100 and 100%, when roots penetrated 30, 60 and 90 cm, respectively. On the other hand, the probability of obtaining corn yields above 4 ton/ha, for the same rooting depths, was 3.3, 16.5 and 65.3%, respectively. The capacity of the soil to store moisture had a large influence on corn yields, both increasing yields and making yields less variable as available moisture in the rooting depth is increased. Deeper soils storing more moisture are expected to reduce year-to-year corn yield variability caused by weather fluctuations.

Corn yield frequencies were also constructed using selected N fertilizer levels. Here all variables but N and R80 in the final yield predicting model were fixed at their avarage values. Corn yields were simulated using five levels of N fertilizer and historic rainfall records for a 31-year period. Figures 18 and 19 show corn yield frequencies for four locations.

It can be observed in these plots that the probability of obtaining a certain yield varies widely, both between selected N fertilizer levels and among locations, for equal levels of applied N. For example, at Silao, for 60 kg of N/ha, the probabilities of obtaining 2.0, 3.0 and 4.0 ton/ha are 100, 63, and 5%, respectively. Comparing the N levels of 30 and 90 kg/ha for the same location, the probabilities of obtaining yields above 3.0 ton/ha are 17% applying 30 kg/ha, and 73% for 90 kg of N/ha. In both N levels (30 and 90 kg/ha), yields of 2.0 ton/ha can be obtained all years; however, for the N level of 30 kg/ha, the probability of having yields above 3.0 ton/ha is zero, whereas applying 90 kg of N/ha this probability still is 47%. Finally, the probabilities of obtaining above 3.0 ton/ha for 90 kg of N/ha at Silao, a low

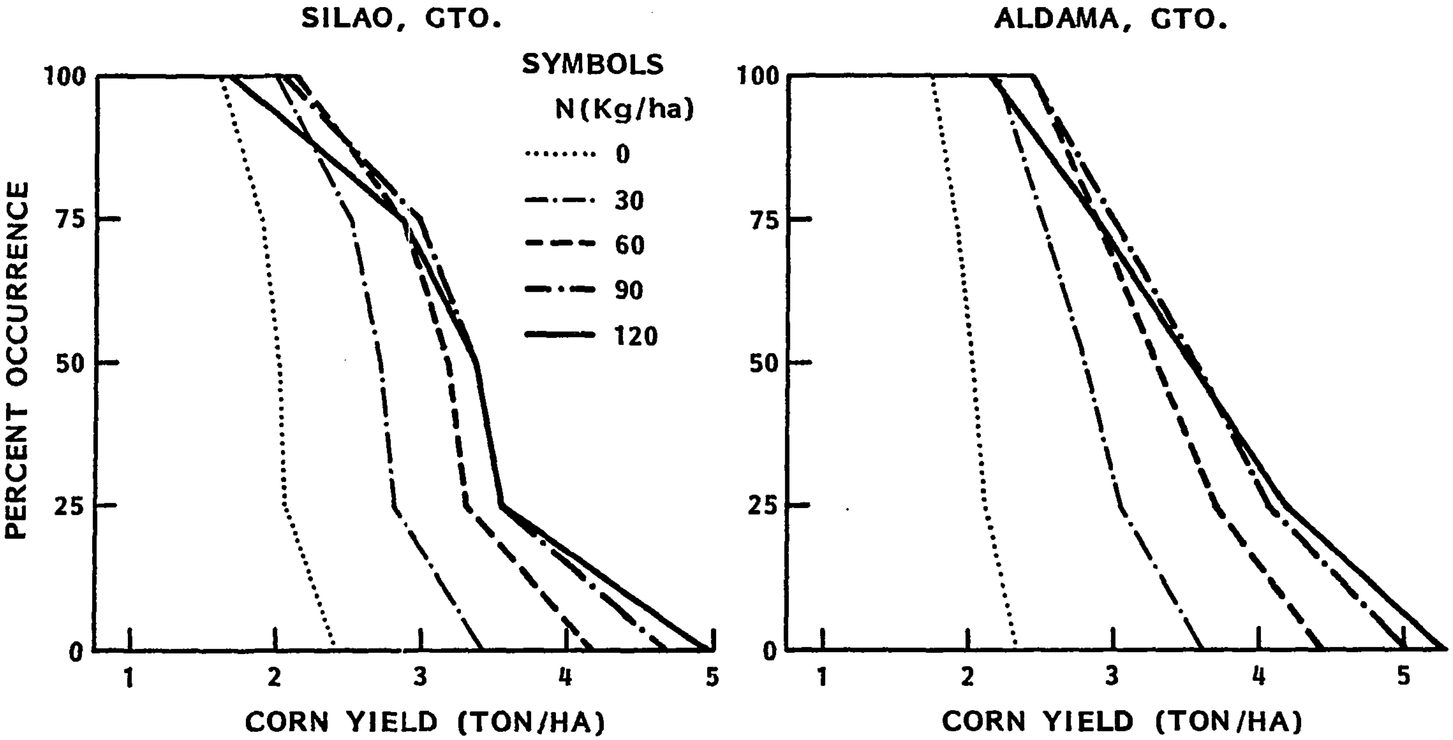

Figure 18. Probability of corn yields above selected values at five levels of nitrogen fertilizer for two locations in the area of study

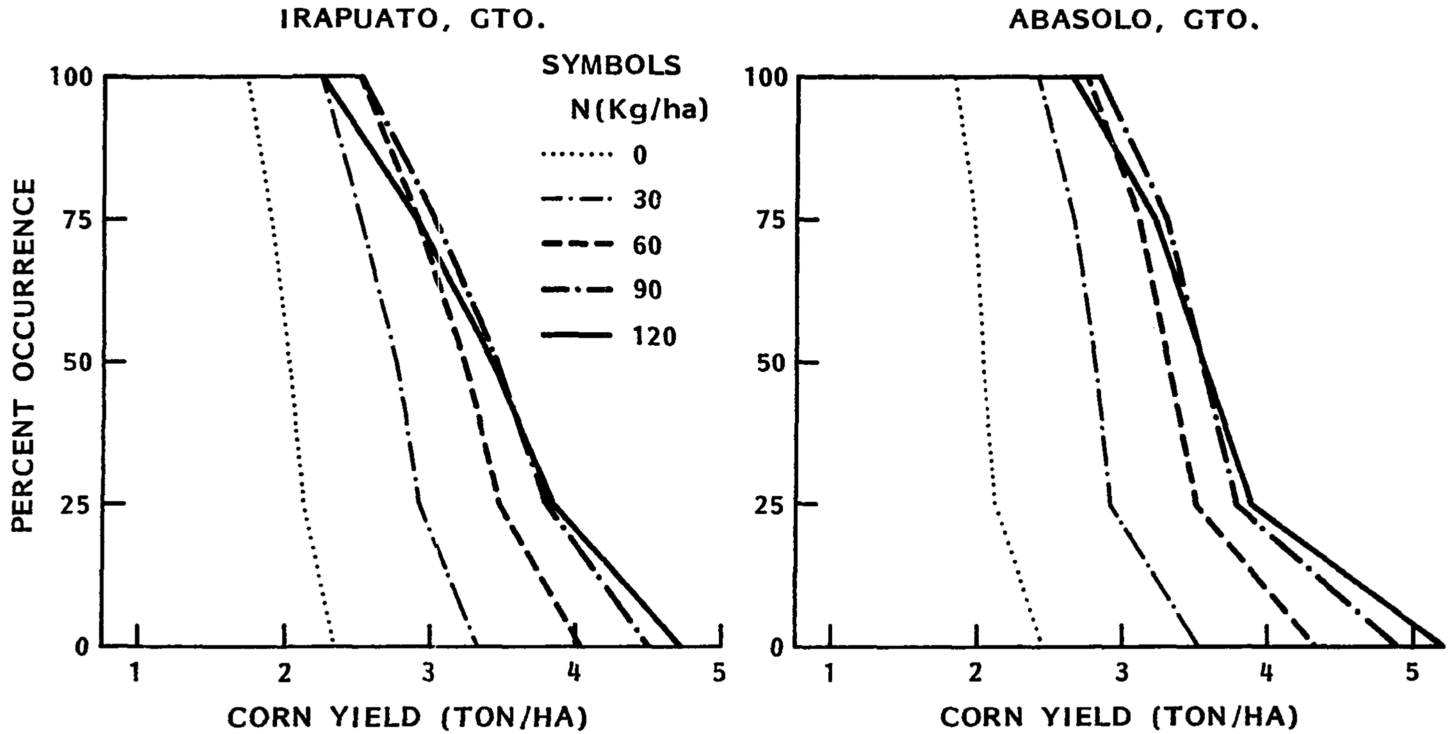

Figure 19. Probability of corn yields above selected values at five levels of nitrogen fertilizer for two locations in the area of study

rainfall location, is 73%, whereas at Abasolo, a location with adequate rainfall, it is 91%.

B. Clay Soils

1. Weather approaches

Weather characterization in the clay-soils area was made according to (1) a soil moisture simulation model by which moisture stress and excess moisture indexes can be computed and (2) the amount of rainfall during critical phenological periods for both an excess and deficit of moisture. As mentioned earlier, rainfall in the clay-soils area is relatively high, which, with the low infiltration rate of these soils, often results in excess moisture becoming a limiting factor to corn yields. It is recognized that periods of water deficit during critical growing stages of corn may occur also. However, these are less frequent. Thus, in this study on clay soils, more attention was given to the problem of excess moisture.

An excess-moisture index, comprising a 108-day period beginning three days after planting date, was first computed. Three aeration levels of 7, 10, and 13% were tested. These results are presented in Table 23. Correlation coefficients computed between yield and each of the three aeration levels showed that 7 and 10% air levels were significant at the 5% level, whereas the excess moisture index with 13% air porosity

Table 23. Simple correlation coefficients between yield and excess moisture indexes for a 108-day period and three aeration levels for clay-soils area

Excess-moisture index	Air level %	r
EM1	7	-.153*
EM2	10	-.184*
EM3	13	-.205**

**,*Significant at the 1% and 5% levels, respectively.

resulted in significance at the 1% level. Based on these preliminary results, the index with 13% air level was selected for further testing.

As mentioned in the Literature Review, excess moisture may have different effects on corn yield, depending on the phenological stage of growth. The 108-day excess-moisture period, beginning three days after planting, was divided into eighteen 6-day periods in order to find the critical period for excess moisture.

Table 24 shows correlation coefficients between yield and excess-moisture indexes for several time periods. It was found that a 54-day period, beginning 15 days after planting date, had the highest correlation (-0.303) with yield. As suggested by Morris (1972) and Loveland (1980), the 54-day excess-moisture index was weighted, giving more weight to

Table 24. Simple correlation coefficients between yield and excess-moisture indexes computed for several time periods for clay-soils area

Excess-moisture index	No. of days beginning 3 days after planting date	No. of days beginning 15 days after planting date	r
EM108	108		-.207**
EM96	96		-.240**
EM66		66	-.288**
EM60		60	-.294**
EM54		54	-.303**
EM54DWN[a]		54	-.266**

[a]Excess-moisture index giving more weight to early stages.

**Significant at the 1% level.

early stages of growth. Coefficients of 0.9, 0.8, 0.7, 0.6, 0.5, 0.4, 0.3, 0.2 and 0.1 were used as weighting factors for each 6-day period. Then, the number of days with excess moisture for each 6-day period was multiplied by its respective factor, to end up with a weighted excess-moisture index. However, this modification did not improve the correlation between yield and excess moisture, as can be observed in Table 24. A possible reason for this is that excess moisture was not intensive enough during early stages of growth to be reflected by this weighting procedure.

Excess-moisture indexes were also tested using the R^2 increment over a base model, as explained earlier. Table 25 shows these results. Here again, a 54-day period beginning 15 days after planting date showed the highest improvement in the R^2 (8.9%) above that of the base model. Excess moisture, as found in this study, showed detrimental effects on corn after two weeks from planting date. Shortly before planting date, moisture in the soil profile is near or below wilting point. After the onset of the rainy season, it takes some time for these soils to become saturated and have any adverse effect on corn growth and subsequent yields.

Estimation of the effect of excess moisture on corn yields was made using total amounts of rainfall during the different phenological periods of corn. The corn-growing season was divided into 6-day periods and the critical period of excess moisture for corn was determined using an iterative process. Correlation coefficients between yield and several rainfall periods are given in Table 26. The same rainfall periods were evaluated using the R^2 increment over a base model as an additional criterion. Results are provided in Table 27. As in the excess-moisture index, the critical period of excess moisture using total amounts of rainfall was found to be 48 days starting 12 days after the planting date. This time period had the highest correlation (-0.297) with yield, which was significant at the 1% level. The R^2

Table 25. R^2 improvement due to addition of excess-moisture indexes to the base yield regression model for clay-soils area

Excess-moisture index	R^2	Improvement in R^2
Base model (Yield = N)	0.605	-
EM108	0.645	0.040
EM96	0.659	0.054
EM66	0.686	0.081
EM60	0.688	0.083
EM54	0.694	0.089
EM54DWN [a]	0.673	0.068

[a]See explanation in Table 24.

Table 26. Simple correlation coefficients between yield and several rainfall periods for clay-soils area

Rainfall period	No. of days after planting date	No. of days after 12 days from planting date	r
R120	120		-.145
R108	108		-.169*
R60		60	-.215**
R48		48	-.297**
R48DWN[a]		48	-.271**

[a]Rainfall period weighted giving more weight to early stages.

**,*Significant at the 1% and 5% levels, respectively.

Table 27. R^2 improvement due to addition of several rainfall periods to the base yield regression model for clay-soils area

Rainfall period[a]	R^2	Improvement in R^2
Base model (Yield = N)	0.604	-
R120	0.625	0.021
R108	0.632	0.028
R60	0.650	0.046
R48	0.693	0.089
R48DWN	0.679	0.075

[a]See explanation of rainfall periods in Table 26.

improvement above that of the base model, for the 48-day critical period, was 8.9% (see Table 27). When this 48-day excess-moisture period was weighted using the same procedure described earlier, no improvement in the R^2 was obtained.

As shown, both approaches to characterize excess moisture were very similar. Both the 54-day excess-moisture index and the 48-day excess rainfall improved the R^2 8.9% above that of the base model. The final R^2, including applied N fertilizer plus the best of the excess-moisture approaches, was 0.693. This means that about 69% of the corn-yield variation was explained by only these two variables.

It was expected that the excess-moisture index would explain yield variations better than total rainfall. There could be several reasons why it did not. First, it is believed that the modifications made to adapt the soil-moisture simulation program were not enough to develop an excess-moisture index more sensitive to yield variation. This means that major modifications using local research are necessary in order to improve such an index. In addition to the rate of transpiration and the potential evapotranspiration/pan evaporation ratio, which have to be developed locally, the infiltration and redistribution of moisture in the soil profile should be considered.

Water deficits in the clay-soils area were characterized using (1) the revised version of the soil-moisture simulation model, by which moisture stress and excess moisture were simultaneously determined, and (2) total amount of rainfall during critical phenological periods. Table 28 shows correlation coefficients between yield and several rainfall periods surrounding silking date. The period comprising 10 days before silking date and 20 days after silking date was found to be the highest correlated with corn yields. The correlation coefficient for this 30-day critical period was significant at the 1% level. Single values of excess-moisture and moisture-stress indexes, as well as total amounts of rainfall for both excess moisture and moisture deficit, for 53 experiments located in the clay-soils area are given in Appendix Table A7.

Table 28. Simple correlation coefficients between yield and several rainfall periods around silking date for clay-soils area

Critical period			
Before silk	After silk	Total	
----------------(days)----------------			r
20	30	50	.083
15	25	40	.176*
10	20	30	.241**
10	15	25	.233**
10	10	20	.228**

**,*Significant at the 1% and 5% levels, respectively.

2. Corn-yield-predicting models

Since the procedure used in developing and testing corn-yield regression models for the clay and light-textured soils was exactly the same, some details relative to the procedure which were discussed earlier are omitted in this section.

a. Development In the clay-soils area, two corn-yield-predicting models were developed, one for each weather-characterization approach used. Tables 29 and 30 show the selected variables, estimates for these variables, as well as the agronomic interpretation of the effect of the variable on yield, for final regression models 4 and 5, respectively.

The R^2 values for models 4 and 5 were 0.81 and 0.84,

Table 29. Yield-prediction model 4 using excess-moisture index (EM54) as an alternative approach to assess the effect of excess moisture and other variables on corn yields for clay-soils area[a]

Variable	Estimate	Interpretation of the effect of the variable on yield
INTERCEPT	1597.61	
N	26.2543**	Yield increased 26.3 kg/ha per kg of nitrogen fertilizer applied
EM54	-39.7043**	Yield decreased 39.7 kg/ha per unit of excess-moisture index
SN	14.6985**	Yield increased 14.7 kg/ha per unit of total soil nitrogen
ROOT	11.8387**	Yield increased 11.8 kg/ha per cm of rooting depth
WEED	-16.5762**	Yield decreased 16.6 kg/ha per unit of weed competition
L	-21.4549**	Yield decreased 21.5 kg/ha per unit of leaf blight

[a]R^2 = 0.81; error mean square = 465,769; error d.f. = 173.

**Significant at the 1% level.

Table 30. Yield-prediction model 5 using rainfall as an alternative approach to estimate the effect of excess moisture (R48), moisture stress (R30), and other variables on corn yields for clay-soils area[a]

Variable	Estimate	Interpretation of the effect of the variable on yield
INTERCEPT	943.38	
N	26.300**	Yield increased 26.3 kg/ha per kg of nitrogen fertilizer applied
R48	-3.342**	Yield decreased 3.3 kg/ha per mm of excess rainfall during the 48-day critical period
R30	3.424**	Yield increased 3.4 kg/ha per mm of rainfall around silking date
SN	22.213**	Yield increased 22.2 kg/ha per unit of total soil nitrogen
ROOT	11.435**	Yield increased 11.4 kg/ha per cm of rooting depth
WEED	-17.406**	Yield decreased 17.4 kg/ha per unit of weed competition
L	-14.198**	Yield decreased 14.2 kg/ha per unit of leaf blight
PH	-28.452**	Yield decreased 28.5 kg/ha per unit of pH

[a]R^2 = 0.84; error mean square = 383,102; error d.f. = 171.

**Significant at the 1% level.

respectively. In addition to the linear effect of applied N and other variables, model 4 included the excess-moisture index (EM54), whereas model 5 included the 48-day critical period of excess rainfall (R48). All selected variables for these two models were significant at the 1% level. Besides applied N fertilizer and the variable to characterize excess moisture, both models included the same soil and environmental variables. Additionally, model 5 included the variables R30 and PH which were also significant at the 1% level. It is interesting to note that the R^2 values for models 4 and 5 for the clay soils were higher than those of the models developed for the light-textured soils. This was due, in part, to the higher correlation between yield and applied N fertilizer observed in the clay soils (see Tables 7 and 8).

Signs for the selected variables in models 4 and 5 were all consistent with scientific knowledge, as can be evidenced by looking at the interpretation of the effect of these variables on yield given in Tables 29 and 30. As a further check, in Table 6, the mean and the range for these variables are presented, which can also be examined. As a way of illustration, Figure 20 shows the relationship between corn yield and excess rainfall during the early 48-day critical period at three nitrogen levels using yield model 5. Other variables included in this model were set at average values. This picture shows that corn yields decrease as excess moisture increases.

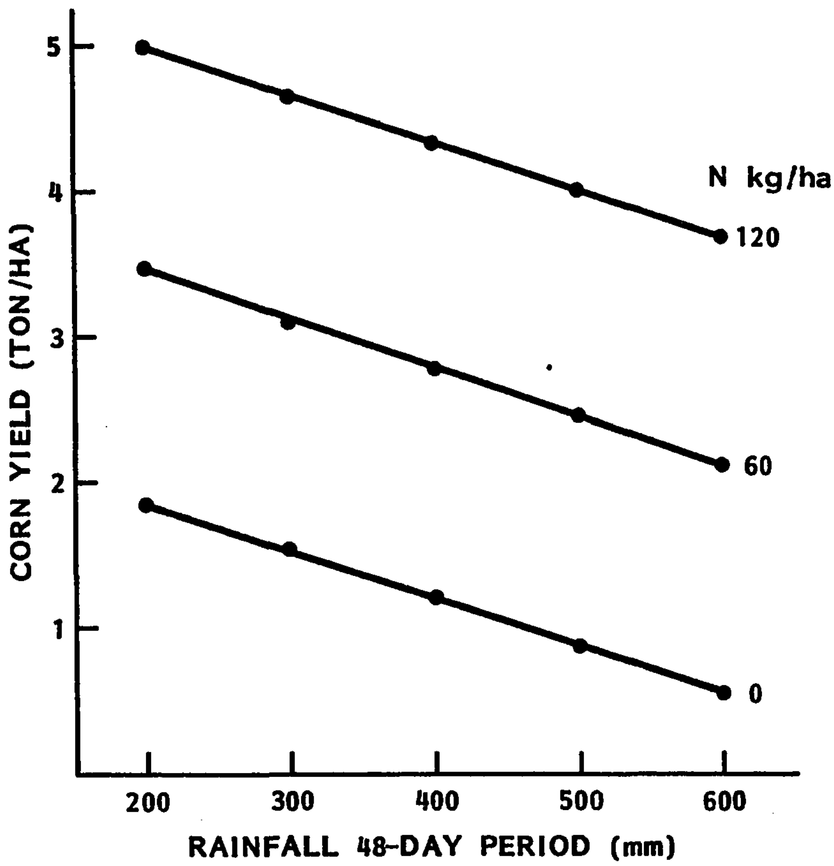

Figure 20. Corn yield decrease due to excess rainfall during the 48-day critical period at three nitrogen levels and at average levels of the other site variables for clay-soils area

Furthermore, since the interaction between applied N fertilizer and excess moisture was not significant, the decrease in yield as excess moisture increases is the same at all N levels. However, it seems that, under high rainfall conditions occurring during the vegetative stage, N levels higher than 120 kg/ha should be applied to the corn crop in order to reduce the detrimental effect caused by excess moisture.

b. Evaluation Corn-yield models developed for the clay-soils area were also evaluated using independent yield data. A total of 32 observations from eight experimental sites taken at random were used for the test. Table 31 shows this evaluation for models 4 and 5. Little difference was found between the two models. Bias for models 4 and 5 was -132 and -185 kg/ha, respectively, which, when expressed on a percentage basis, was -4.2% and -5.8%. These departures from zero bias (0%) can be considered low. A negative bias, as mentioned earlier, indicates underestimation of yields by the predicting model.

The average errors in corn-yield predictions as estimated by the standard deviation were 539 kg/ha (8.6 bu/A) and 584 kg/ha (9.3 bu/A) for models where rainfall and the excess-moisture index were included, respectively. Relative standard deviation for models 4 and 5 were 19.2 and 18.0%, respectively.

Table 31. Evaluation of corn-yield-prediction models using 32 observations from 8 experimental sites omitted from original data used in developing yield prediction models for clay-soils area

Experimental site	N kg/ha	Actual yield kg/ha	Model 4 $\hat{Y}_4$-Yield	Model 5 $\hat{Y}_5$-Yield[a]
207	0	2410	-290	-644
	40	3780	-663	-1014
	80	4020	95	-255
	120	4830	283	-69
217	0	3270	-613	-1017
	40	4200	-545	-948
	80	3870	782	381
	120	4560	1090	690
219	0	1170	620	658
	40	2740	121	162
	80	3770	162	204
	120	4300	703	747
222	0	1020	124	184
	40	2870	-633	-571
	80	4080	-751	-687
	120	4620	-199	-133
319	0	310	394	513
	40	1460	284	404
	80	2870	-87	36
	120	3720	103	227
418	0	1740	-57	24
	40	4070	-1337	-1250
	80	4940	-1157	-1071
	120	5270	-437	-349
512	0	930	291	-90
	40	1810	440	61
	80	3210	70	-308
	120	4350	-41	-417

[a]Corn yield differences between estimated yield ($\hat{Y}_i$) for yield models 4 and 5 and actual yield.

Table 31. (Continued)

Experimental site	N kg/ha	Actual yield kg/ha	Model 4 $\hat{Y}_4$-Yield	Model 5 $\hat{Y}_5$-Yield
515	0	1340	-685	-291
	40	2350	-708	-312
	80	3490	-861	-463
	120	4350	-734	-334
Bias (kg/ha)			-132	-185
Relative bias (%)			-4.2	-5.8
Standard deviation (kg/ha)			584	539
Relative standard deviation (%)			19.2	18.0
Correlation between $\hat{Y}_i$ and Yield (Y)			0.91	0.92

The relationships between actual yields vs predicted yields for corn-yield models 4 and 5 are given in Figures 21 and 22, respectively. These plots included 32 independent yield-data points, which were omitted from original data used in developing the yield-prediction models. The agreement between actual yields (Y) and predicted yields ($\hat{Y}$) was high, as shown by the correlation coefficients of 0.91 and 0.92 obtained for models 4 and 5, respectively. This is another criterion that may be used, in addition to bias and standard deviation, to judge how well a yield-regression model can predict crop yields when independent yield-data sets are employed.

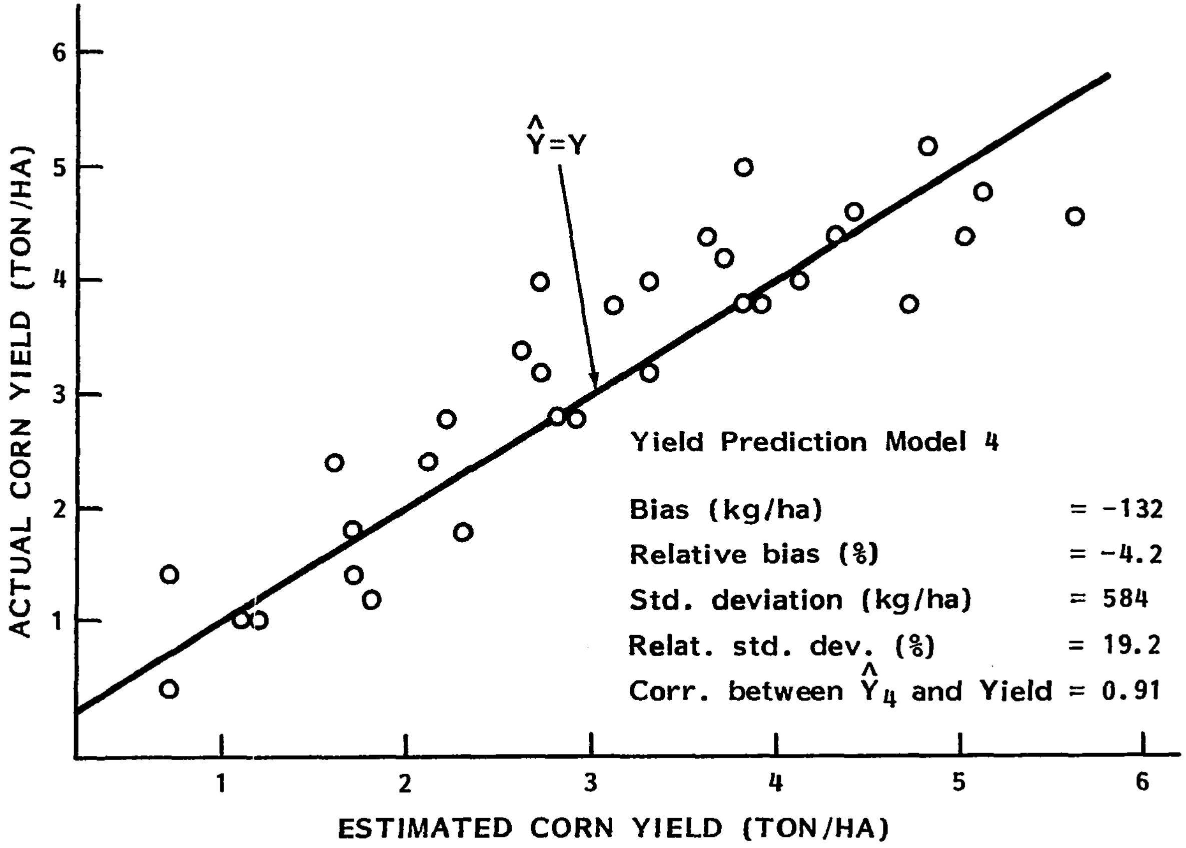

Figure 21. Actual corn yield vs estimated corn yield with excess-moisture index included in the yield prediction equation for clay-soils area

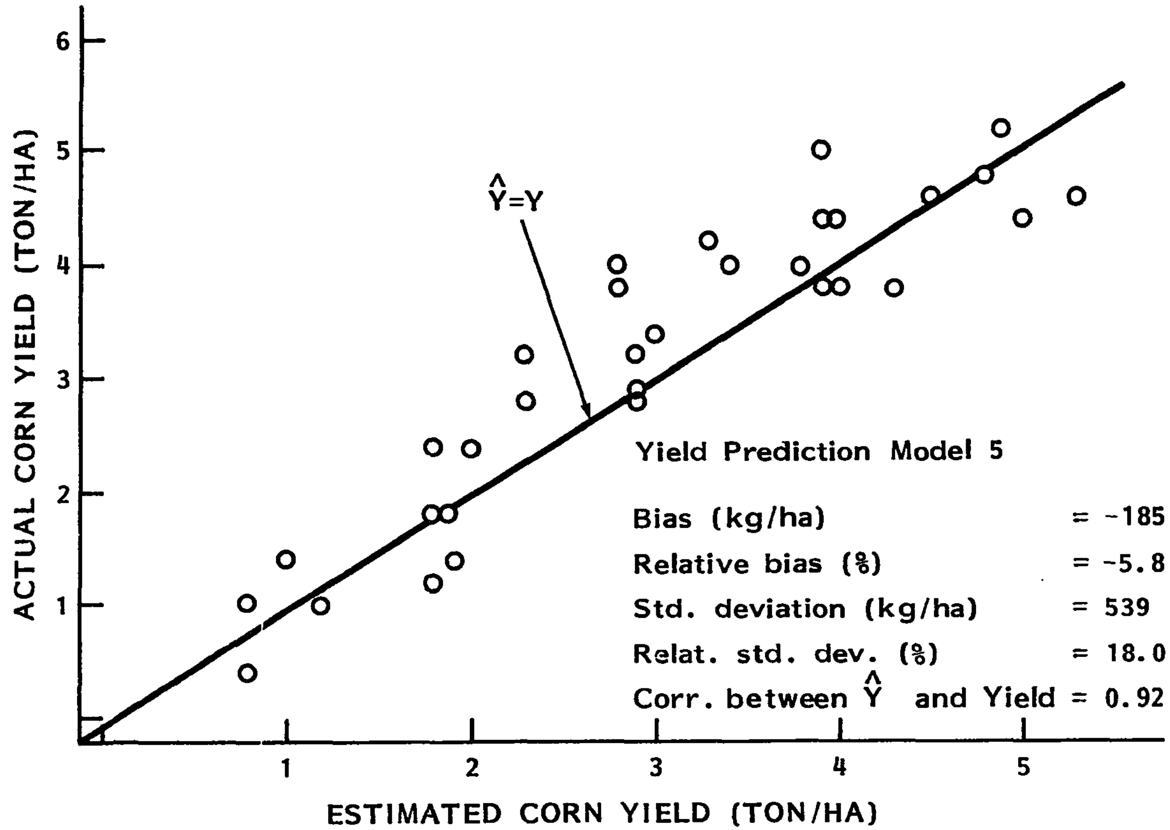

Figure 22. Actual corn yield vs estimated corn yield with rainfall included in the yield prediction equation for clay-soils area

Corn-yield differences between predicted yields and actual yields in the clay-soils area were also evaluated using a variance component method as discussed earlier. Analyses of variance to compute variance components between experimental sites and within sites for models 4 and 5 are presented in Table 32. The between sites variance component accounted for 41.1 and 29.9% of the yield variation observed between experimental sites for yield differences of models 4 and 5, respectively; whereas, 58.9 and 70.1% of that yield variance was explained by the within sites variance component, that is, by differences of N fertilizer levels employed in each experimental site. These results showed that models 4 and 5 were more sensitive to detect yield differences between the N fertilizer treatments used, that is, within sites, as reflected by the high percentage (58.9 and 70.1%) of the within sites variance component. In other words, more yield variation was caused by differences in N fertilizer levels, rather than by site differences, which were less variable.

3. Simulation of corn yields

In order to simulate corn yields for the clay-soils area, using historic weather records, corn-yield predicting model 5 was chosen. This model was selected because it resulted in slightly better predictions of corn yields than model 4, as shown in the previous section. Model 5 was reestimated

Table 32. Variance components of the differences between actual (Y) and predicted yield ($\hat{Y}_i$) for the two yield models developed for the clay-soils area

Variance source	d.f.	Expected mean squares			
		Sum of squares	Mean squares	Variance component	%
		Model 4 (DIFF $\hat{Y} - Y_4$)			
Total	31	10,573	341	355	100.0
Between sites	7	5,554	793	146	41.1
Within sites (Error)	24	5,019	209	209	58.9
		Model 5 (DIFF $\hat{Y} - Y_5$)			
Total	31	8.993	290	299	100.0
Between sites	7	3,966	567	89	29.9
Within sites (Error)	24	5.027	209	209	70.1

using all available data (53 experimental sites). This reestimated model is given in Table 33. The R^2 value (0.84), as well as signs for the regression coefficients of the variables in the reestimated model, remained the same as those of model 5, presented in Table 30. The magnitudes of estimates were very similar in both models. To simplify the model, the variables SN, WEED, L and PH were set at their average values. Since the quadratic effect of applied N was not significant, N was set at 120 kg/ha, which was the highest level tested.

Table 33. Reestimated final yield-prediction model using rainfall (including all experimental sites) to estimate the effect of excess moisture (R48), moisture stress (R30), and other variables on corn yields for clay-soils area[a]

Variable	Estimate	Interpretation of the effect of the variable on yield
INTERCEPT	1033.20	
N	25.084**	Yield increased 26 kg/ha per kg of nitrogen fertilizer applied
R48	-3.250**	Yield decreased 3.2 kg/ha per mm of rainfall during the 48-day critical period
R30	3.796**	Yield increased 3.8 kg/ha per mm of rainfall around silking date
SN	21.498**	Yield increased 21.5 kg/ha per unit of total soil nitrogen
ROOT	10.754**	Yield increased 10.7 kg/ha per cm of rooting depth
WEED	-18.107**	Yield decreased 18.1 kg/ha per unit of weed competition
L	-15.445**	Yield decreased 15.4 kg/ha per unit of leaf blight
PH	-31.767**	Yield decreased 31.8 kg/ha per unit of PH

[a]R^2 = 0.84; error mean square = 369,642; error d.f. = 203.

**Significant at the 1% level.

Then, two rooting depths, 60 and 120 cm, were replaced one at a time in the predicting model, and finally, values for variables R48 and R30 were substituted in the model using historic rainfall records. In this way, corn yields were simulated at two rooting depths for several locations in the clay-soils area.

Figures 23, 24 and 25 show corn-yield frequencies for six locations and two rooting depths. Single values of simulated corn yields are given in Tables A8 and A9 in the Appendix. The increase in corn yields with increased rooting depth from 60 to 120 cm is obvious. The frequency with which corn yields greater than 4.0, 4.5 and 5.0 ton/ha occurred, taking the average of six locations, was 81.2, 34.0 and 4.8% when corn roots penetrate 60 cm. However, when rooting depth penetrates to a depth of 120 cm, these frequencies increased to 98.7, 89.2 and 51.5% for the same levels of corn yields. This demonstrates that increasing rooting depth not only increases corn yield, but also the probability of obtaining such a yield.

Locations used to simulate corn yields showed different degrees of corn yield variability. The standard deviations for simulated corn yields at Atotonilco, Jal. was 503 kg/ha, whereas that found for corn yields at Abasolo, Gto. was only 315 kg/ha. The average standard deviation for simulated corn yields of six locations in the clay-soils area was 404 kg/ha.

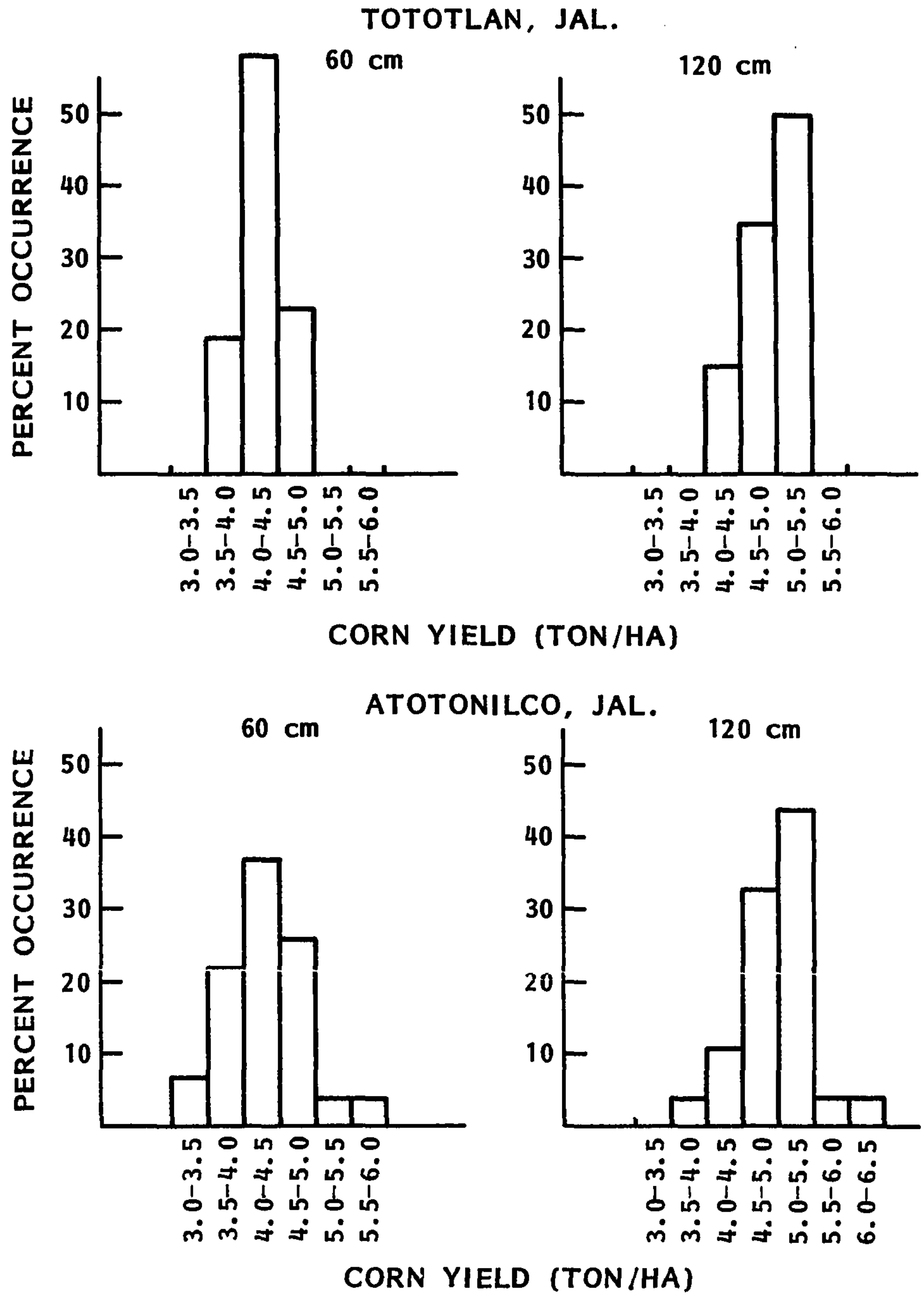

Figure 23. Relative frequency diagrams of corn yield using 120 kg of N/ha at two rooting depths for two locations in the area of study

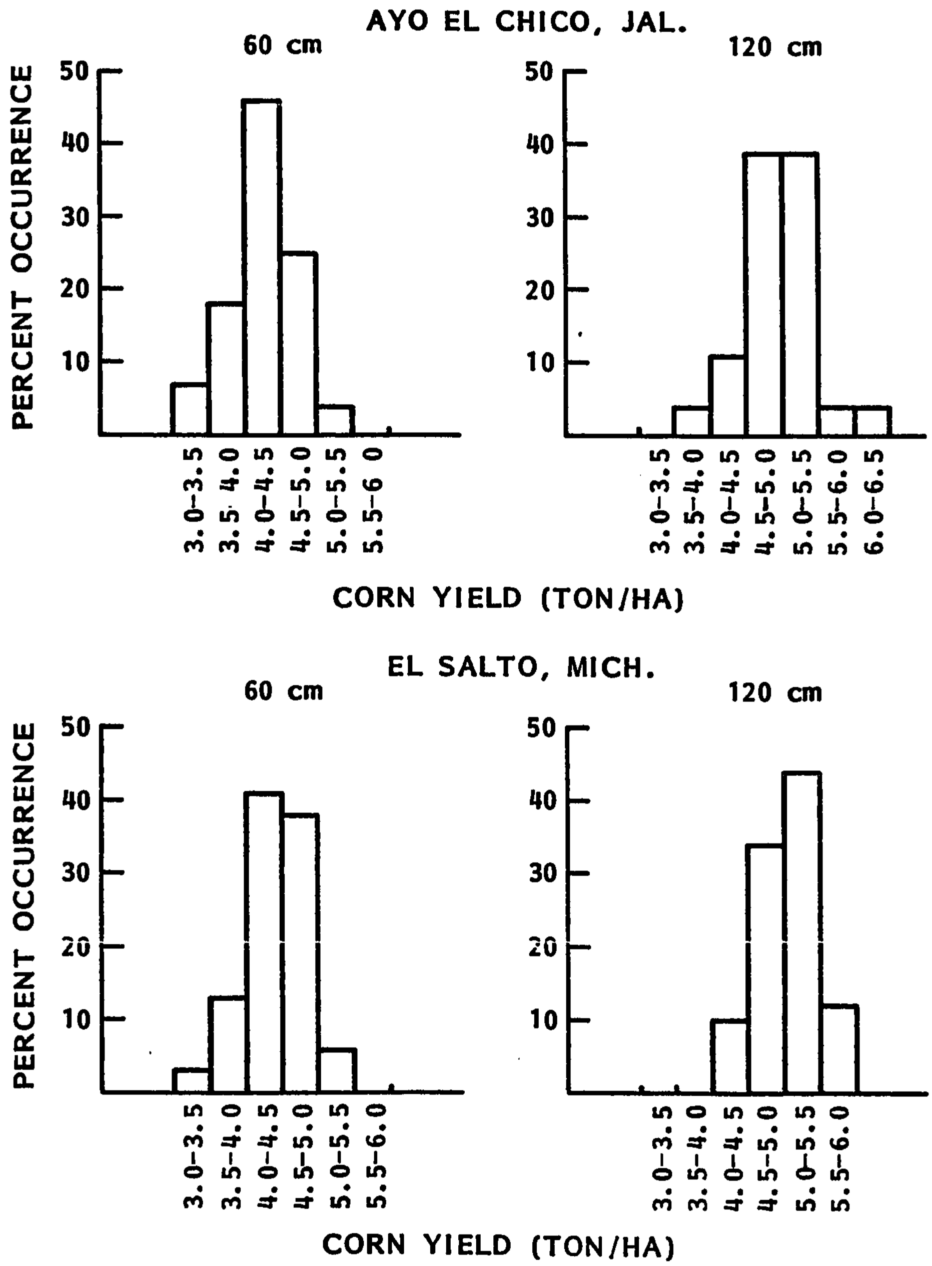

Figure 24. Relative frequency diagrams of corn yield using 120 kg of N/ha at two rooting depths for two locations in the area of study

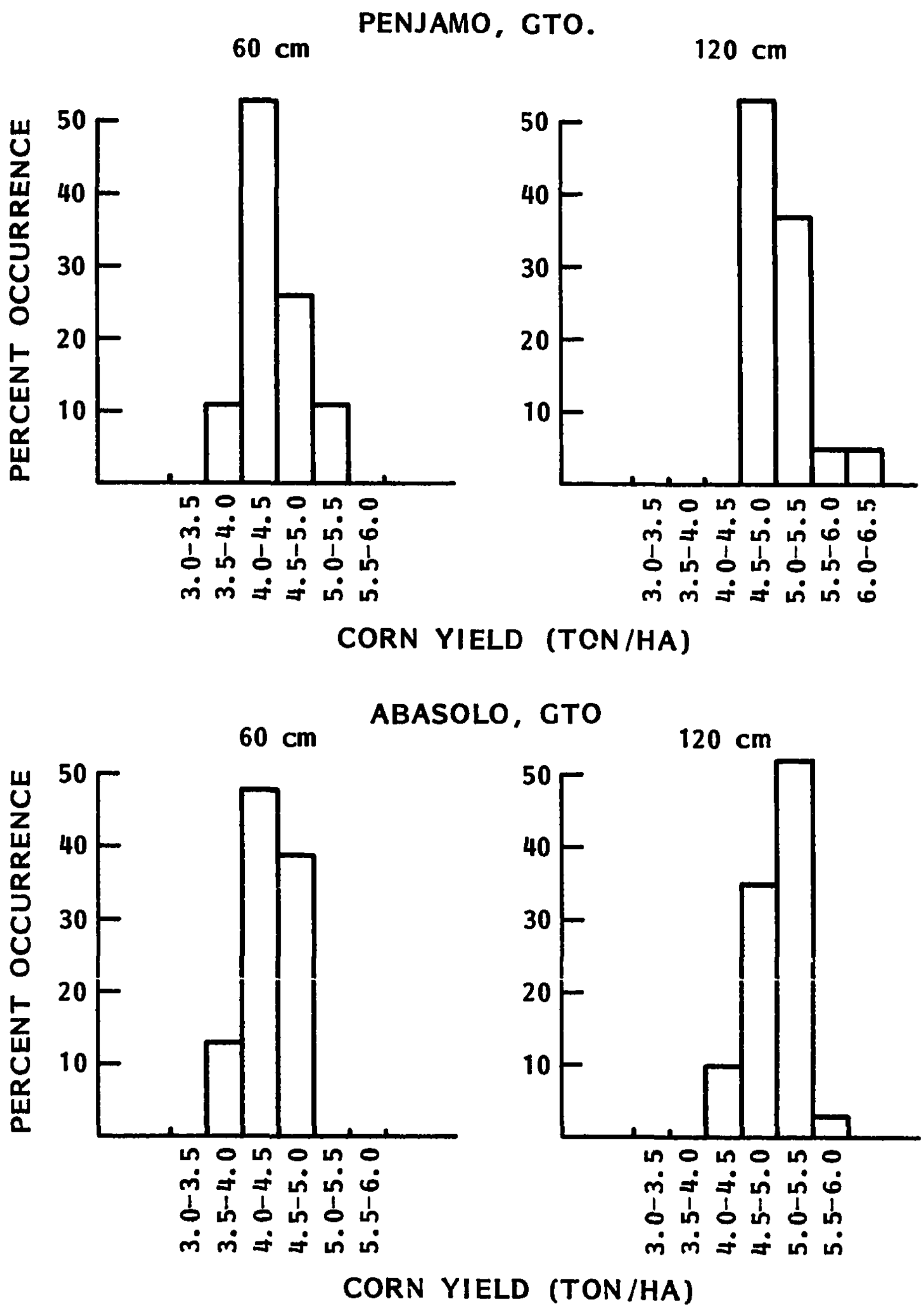

Figure 25. Relative frequency diagrams of corn yield using 120 kg of N/ha at two rooting depths for two locations in the area of study

Annual variability in corn yields decreased with increased rooting depth. Coefficients of variation (C.V.), taking the average of six locations, equalled 9.3 and 8.1% for rooting depths of 60 and 120 cm, respectively. Corn yields were also less variable in the clay-soils area, as compared with simulated corn yields for the light-textured soils area. The overall standard deviation in the former area was 514 kg/ha, whereas in the latter, it was only 404 kg/ha. These figures could be interpreted to mean that soil and climatic conditions present in the clay-soils area are, in general, more adequate to produce higher and less variable corn yields than those found in the northern part of the area of study.

V. SUMMARY AND CONCLUSIONS

The objectives of this research were (1) to test different approaches to characterize the relationship between weather and corn yields and (2) to develop yield models to simulate corn yields and optimal nitrogen rates for two soil groups using historic weather records.

Experimental yield data used in this study came from 77 simple fertilizer trials, which were carried out with unirrigated corn in farmers' fields in the El Bajio area of central Mexico during the period of 1962-1965. Field experiments consisted of four levels of N fertilizer and three levels of phosphorus fertilizer. However, to calibrate the corn-yield models developed in this research, corn yields from only four treatments (0-60, 40-60, 80-60, and 120-60 kg of N and P_2O_5/ha, respectively) were used. Each treatment represented the average yield of four replications.

In order to facilitate the study of the relationship between weather and yield, the area of study was divided in two parts: (1) clay-soils area, in which precipitation is relatively high and (2) light-textured soils area, in which rainfall is lower than in the clay-soils area. Weather characterization of these areas was made according to (1) a soil-moisture simulation model (Shaw, 1963) by which moisture stress and excess moisture indexes can be computed, (2) the amount of rainfall during critical phenological periods, for both deficit and excess moisture, and (3) a plant-wilting index (Laird, 1968) which is based on visual symptoms of wilting.

To adapt the soil-moisture simulation model to the area of study in central Mexico, modifications of the following were made: (1) silking date, (2) reestimation of plant-available-water capacity, (3) starting soil moisture, (4) rooting extraction pattern to fit the different corn-rooting depths observed in the area, (5) evaporation rate for the top 6-inch layer, and (6) excess-moisture index. In order to determine the critical air porosity level of the soil and phenological period for corn, air porosity levels of 7, 10 and 13%, and different growing periods were tested.

The different approaches used to characterize weather were tested to determine their ability to explain yield variation. Correlation and regression techniques were used to evaluate these approaches.

In addition to the applied nitrogen fertilizer and the weather factor, additional soil and environmental variables were included in developing corn-yield regression models for the area of study. In the light-textured soils area, three yield models were developed, one for each weather characterization approach used. In the clay soils, only two yield models were developed, one for each weather approach used.

In building the regression models, a quadratic function was used to approximate the effect of independent variables on yield. Since corn-yield models were developed mainly to predict corn yields using independent data, only those variables well represented in the area of interest were considered. An agronomic criterion was employed in making this *a priori* selection. In order to arrive at the final model for each weather approach, a 5% level of significance was established for the variables that should be included in each of these multiple regression models.

The five corn-yield-predicting models developed in this study were evaluated using independent yield data. Yield-predicting models were evaluated using the differences between actual yield and predicted yield, according to some of the criteria suggested by Wilson and Sebaugh (1981). These criteria included bias, relative bias, standard deviation, relative standard deviation, and the correlation coefficient between actual and predicted yields. Corn-yield differences between estimated and actual yield were additionally evaluated by means of a variance component method. Using this procedure, corn-yield differences caused by two sources of variation (between experimental sites and within sites) can be estimated.

Correlation coefficients between yield and three weather approaches used in the light-textured soils were -0.378 for moisture stress index (MS7); 0.461 for rainfall (R80) (total rainfall for a 80-day period, 55 days before silking and 25 days after silking); and -0.537 for wilting plant index (WPI) which comprised 39 days before silking and 30 days after silking. All correlation coefficients were significant at the 1% level. A high correlation among the weather approaches was observed, especially that between R80 and WPI which reached a value of -0.832. Weather approaches were also evaluated according to the R^2 improvement to a base regression model (yield = $f(N + N^2)$). WPI had the highest R^2 (0.616) which increased the R^2 37.7% above that of the base model. Thus, the best approach to characterize weather in the light-textured soils was WPI, which is a visual method to estimate the degree of wilting in corn plants, followed by R80, and then MS7.

In order to obtain an adequate weather characterization using a moisture-stress index, major modifications in the soil-moisture simulation program have to be made. Among the possible modifications, those of special importance are (1) the rate of corn transpiration, (2) the potential evapotranspiration/pan evaporation ratio through the growing season, and (3) the rooting extraction schedule. Thus, it will be necessary to carry out local research in order to develop these basic relationships necessary to adapt the soil-moisture-simulation program to the area of study in Mexico.

The R^2 values for yield regression models developed for the light-textured soils ranged from 0.58 for model 1, where MS7 was included, to 0.74 for model 3, where WPI was included in addition to other variables. Signs for the estimates of the selected variables in each yield model were all consistent with scientific knowledge. In addition to applied N fertilizer and the corresponding weather factor, all models included soil nitrogen (SN) and available soil moisture in rooting depth (PAWC7). Only model 2 included the variable, days from planting to silking date (SILK).

Evaluation of corn-yield-predicting models for the light-textured soils indicated a negative bias for all models. Bias varied from -183 to -450 kg/ha, which indicates that corn yields tend to be underestimated by these models. The accuracy of predicting corn yields, evaluated by the standard deviation, ranged from 374 kg/ha (5.8 bu/A) for model 3 to 621 kg/ha (9.7 bu/A) for model 1. Predicting error for model 2 with rainfall (R80) included was 426 kg/ha (6.8 bu/A). Correlation coefficients between estimated yield by these models and actual yield were high, ranging from 0.85 to 0.93. Corn yield model 3 was able to explain the most yield variation (54.3%), within experimental sites (among N fertilizer levels), than the other models (12.9 and 23.0% for models 1 and 2, respectively).

In the light-textured soils area, annual optimal N rates were simulated using corn-yield-predicting model 2 for a 31-

year period of weather data. Model 2 was used because of the high correlation between R80 and WPI (r = -0.83) and because there was little difference in corn-yield predictions between this model and model 3. In addition, long-term rainfall records were available. In order to estimate the optimum N rate for corn that maximizes returns from a given investment over a long term, a weighting procedure which makes use of rainfall probabilities was employed. Using this procedure, optimum N rates for four locations in this area were computed. These were very similar, ranging from 73 kg of N/ha for Silao to 84 kg of N/ha for Abasolo.

Corn yields for three rooting depths and several locations in the light-textured soils were simulated using historic weather records. The optimal N rate determined for each location was used to replace N in the yield model. Other variables in the model were held at average values. Corn yields increased and were more stable as rooting depth increased from 30 cm to 90 cm. The reliability of obtaining corn yields above 2 ton/ha, taking the average of four locations, was 93.5% and 100% when roots penetrate 30 cm and 90 cm, respectively. However, yields above 4 ton/ha for the same rooting depths can be obtained in only 3.3% and 65.3% of the cases, respectively. Thus, it can be concluded that the capacity of the soil to store moisture had a large influence on corn yields, both increasing yields and making yields less variable as available moisture in the rooting depth is increased.

In the clay-soils area, the weather approaches to characterize excess moisture were very similar. In both approaches, the critical period of excess moisture was found to be early during the vegetative stage of corn. A 54-day period beginning 15 days after planting date had the highest correlation (r = -0.303) with yield, when an excess moisture index was used. The best air porosity level for this excess index was 13%. When rainfall amounts were used to characterize excess moisture, a 48-day period starting 12 days after planting date was found to be the highest correlated with yield (r = -0.297). Both the 54-day excess-moisture index and the 48-day excess rainfall improved the R^2 8.9% above that of the base model. The R^2 including applied N fertilizer plus any of the excess-moisture approaches was 0.693.

In order to improve the relationship between yield and excess-moisture index, the rate of transpiration, the potential evapotranspiration/pan evaporation ratio, as well as the infiltration and redistribution of moisture in the soil profile should be considered for further research in the area of study.

The R^2 values for models 4 and 5, developed for the clay-soils area were 0.81 and 0.84, respectively. In addition to the linear effect of applied N fertilizer and other variables, model 4 included the excess-moisture index (EM54), whereas model 5 included the 48-day critical period of excess rainfall (R48). All selected variables for these models were significant at the 1% level. Signs for the selected variables in models 4 and 5 were all consistent with scientific knowledge.

Corn-yield models developed for the clay-soils area were also evaluated using independent yield data. Little difference was found between the two models. The average errors in corn-yield predictions, as estimated by the standard deviation, were 539 kg/ha (8.6 bu/A) and 584 kg/ha (9.3 bu/A) for models where rainfall and excess-moisture index were included, respectively.

Models 4 and 5 were more sensitive to detect yield differences between N fertilizer levels (within sites) than between sites, where yield differences were less variable.

Corn yields for several locations and two rooting depths in the clay-soils area were simulated using corn-yield-predicting model 5. Historic weather records from six weather stations were used. Corn yields were simulated using a N fertilizer rate of 120 kg/ha. Other variables in the model were held at average values. As found in the light-textured soils, increasing rooting depth from 60 cm to 120 cm increased corn yields and the probability of obtaining such yields.

In addition, annual variability in corn yields decreased with increased rooting depth. The frequency with which corn yields greater than 5.0 ton/ha occurred, taking the average of six locations, was only 4.8% when roots penetrate 60 cm. However, when rooting depth penetrates to a depth of 120 cm, this frequency increased to 51.5%. Locations used to simulate corn yields in the clay-soils area showed different degrees of corn-yield variability.

Corn yields were less variable in the clay-soils area, as compared with those for the light-textured soils area. The overall standard deviation in the former area was 514 kg/ha, whereas in the latter, it was only 404 kg/ha. It can be concluded, then, that soil and climatic conditions prevailing in the clay-soils area are, in general, more adequate to produce higher and less variable corn yields than those present in the northern part of the area of study.

It must be noted that many assumptions were made in this study. This was especially evident in adapting the soil-moisture simulation program to compute moisture-stress and excess-moisture indexes for the area of study. The results obtained in this research indicate that some basic soil-plant-environment relationships must be developed first, through local research, before attempting to use this method in a region different than Iowa.

Although the results obtained in dividing the area of study in two parts allowed the use of simpler approaches to characterize weather, this reduced the amount of available data to use in developing and testing corn-yield models. It is advisable that further testing for the best models for each area, using more data, be done.

It is recognized there are shortcomings of the weather data used in this study, which could be a weak element in the corn-yield-predicting models developed through this research. However, according to the available weather data, the approaches used for weather characterization are believed to be useful to use in regions where weather becomes the most limiting factor to crop yields.

Finally, nitrogen fertilizer recommendations obtained using simulation techniques like those used here, as well as crop yield simulations, could be made for any soil and climate if several years of data on crop response to N fertilizer, or other agronomic practices, and the necessary weather data are available.

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VIII. APPENDIX

Table A1. Some soil properties and slope of land where the experiments were conducted

Expt. no.	Plow layer (0-15 cm) pH	Total N	Organic matter	Clay content	Soil type[b]	Bulk density g/cm³	PAWC[a] mm of H_2O	Rooting depth cm	Land slope %
		--------	%	--------					
202	6.8	0.087	1.74	60	C	1.25	52	60	0.1
203	7.0	0.076	1.69	66	C	1.25	39	50	5.5
204	6.8	0.120	2.32	58	C	1.25	84	90	8.0
206	6.5	0.087	1.52	53	C	1.30	56	50	3.0
207	6.8	0.073	1.12	40	C	1.30	96	80	3.0
208	7.2	0.120	2.32	48	C	1.25	167	120	0.1
209	8.2	0.076	1.88	58	C	1.25	112	120	2.0
210	7.8	0.076	1.60	61	C	1.25	76	90	2.0
211	7.0	0.078	1.16	20	L	1.45	37	25	8.0
212	6.9	0.055	1.07	66	C	1.30	104	120	0.1
213	6.5	0.054	1.27	58	C	1.30	87	100	0.2
216	6.6	0.078	1.29	62	C	1.25	93	120	0.1
217	7.6	0.095	1.62	59	C	1.25	93	90	0.2
218	7.8	0.094	1.59	55	C	1.25	69	75	0.3
219	7.4	0.095	1.60	52	C	1.30	64	55	0.5
220	7.4	0.078	1.76	59	C	1.25	72	80	0.2
221	7.2	0.099	1.81	52	C	1.25	140	120	0.1
222	7.0	0.069	1.62	60	C	1.25	57	60	2.0
227	6.3	0.060	1.86	32	L	1.35	81	65	4.0
228	8.2	0.081	1.41	56	C	1.30	48	50	0.1
229	7.6	0.078	1.27	57	C	1.25	44	45	0.1
232	7.9	0.087	1.52	32	L	1.40	79	50	0.2
301	7.4	0.105	1.38	17	L	1.40	61	50	0.2
302	5.6	0.098	1.32	12	L	1.45	41	38	2.6
303	5.9	0.103	1.04	17	L	1.35	42	35	1.1
304	6.0	0.075	1.12	13	L	1.35	53	50	2.8
306	8.0	0.090	1.30	27	L	1.40	138	80	0.5
307	5.8	0.085	0.85	13	L	1.40	72	60	2.1
308	7.1	0.083	1.02	57	C	1.25	68	55	0.4
309	6.6	0.063	1.25	48	C	1.25	156	120	0.5
310	6.7	0.137	1.90	57	C	1.25	66	55	7.4
311	6.6	0.085	1.61	63	C	1.25	65	75	2.6
312	6.6	0.100	1.46	52	C	1.30	67	55	1.7
313	7.0	0.120	1.62	58	C	1.25	77	75	1.7

[a]Plant-available-water capacity estimated at rooting depth, using texture components.

[b]Soils with clay content >35% at rooting depth were grouped into the clay soils area (C) and soils with clay content ≤35% were included in the light-textured soils area (L).

Table A1. (Continued)

Expt. no.	pH	Total N	Organic matter	Clay content	Soil type	Bulk density g/cm³	PAWC mm of H_2O	Rooting depth cm	Land slope %
	Plow layer (0-15 cm)								
		-----	%	-----					
314	7.8	0.090	1.58	54	C	1.25	101	90	0.2
315	6.9	0.100	1.58	65	C	1.25	71	80	3.5
316	7.4	0.073	1.05	57	C	1.25	137	120	1.6
318	7.0	0.100	2.47	41	C	1.25	185	120	0.3
319	8.0	0.092	1.68	65	C	1.25	109	120	3.5
320	7.4	0.090	1.66	45	C	1.33	91	65	0.3
321	7.9	0.100	1.68	61	C	1.25	119	120	2.0
322	6.2	0.090	1.66	45	C	1.33	91	65	0.3
323	7.3	0.113	1.69	55	C	1.25	73	65	1.7
402	6.4	0.046	0.57	15	L	1.40	39	40	2.3
405	6.3	0.072	1.08	10	L	1.35	64	60	0.9
406	6.5	0.056	0.64	14	L	1.35	52	60	3.1
408	6.8	0.064	1.00	25	L	1.35	72	50	1.4
409	6.0	0.075	1.22	17	L	1.30	67	65	2.3
410	6.0	0.095	1.52	18	L	1.35	86	70	2.1
411	5.4	0.113	1.90	24	L	1.35	42	32	4.0
412	5.9	0.046	0.60	24	L	1.40	48	35	1.7
413	6.3	0.060	1.00	15	L	1.30	48	55	1.9
414	6.9	0.047	0.81	61	C	1.25	87	90	0.7
415	6.9	0.059	1.30	53	C	1.25	118	110	1.2
416	6.9	0.072	1.57	59	C	1.25	42	40	0.3
417	6.9	0.061	1.16	54	C	1.25	98	90	1.2
418	7.3	0.081	1.33	61	C	1.25	50	60	2.3
419	7.0	0.129	2.41	59	C	1.25	50	55	3.8
420	6.8	0.075	1.76	67	C	1.25	66	80	0.2
421	7.2	0.058	1.22	64	C	1.25	43	50	1.7
422	6.8	0.084	1.85	59	C	1.25	73	75	2.1
423	7.1	0.123	2.15	60	C	1.25	41	42	2.8
501	7.0	0.087	0.96	13	L	1.40	165	120	0.2
503	8.3	0.124	1.60	35	L	1.34	110	72	0.4
504	8.1	0.101	1.37	21	L	1.36	137	85	1.4
505	6.3	0.099	1.21	9	L	1.34	39	55	1.7
506	6.4	0.069	0.76	13	L	1.38	79	60	3.8
507	6.6	0.105	1.21	17	L	1.35	83	73	1.7
508	7.3	0.094	1.30	63	C	1.26	110	120	0.4
509	7.6	0.077	0.87	56	C	1.28	137	120	0.9
510	7.3	0.058	1.64	49	C	1.30	102	80	0.5
511	7.4	0.054	0.87	37	C	1.33	89	70	2.4
512	7.4	0.074	1.86	51	C	1.29	89	80	2.6
513	6.6	0.111	2.05	43	C	1.31	70	55	1.9
514	7.2	0.125	2.25	53	C	1.28	129	110	0.9
515	7.0	0.084	1.60	62	C	1.26	54	60	3.0
516	7.0	0.067	1.57	67	C	1.24	69	90	2.6

Table A2. Corn yields for the four treatments used in this dissertation, obtained from 77 field experiments carried out during 1962-1965; yields are expressed in metric tons per ha of grain at 15.5% moisture

Experiment number	Fertilizer treatment, $N\text{-}P_2O_5$, kg/ha			
	0-60	40-60	80-60	120-60
202	1.94	3.54	4.71	5.36
203	0.46	1.18	1.82	2.19
204	1.89	3.86	5.00	5.70
206	1.62	3.53	3.64	3.84
207	2.41	3.78	4.02	4.83
208	3.27	4.59	5.63	5.99
209	0.61	2.38	3.77	4.43
210	0.84	2.17	3.56	3.91
211	1.38	2.95	4.13	4.10
212	0.57	2.93	4.37	5.75
213	1.81	3.28	4.18	4.34
216	2.06	3.31	4.39	5.47
217	3.27	4.20	3.87	4.56
218	1.49	3.12	4.88	5.40
219	1.17	2.74	3.77	4.30
220	1.03	3.05	4.50	5.70
221	3.63	4.66	6.12	6.48
222	1.02	2.87	4.08	4.62
227	2.08	3.95	4.25	4.50
228	1.82	3.18	4.16	4.40
229	1.08	2.13	2.76	2.79
232	2.68	3.07	3.04	2.90
301	1.28	1.50	1.46	1.16
302	1.98	2.44	2.14	2.17
303	1.88	2.83	2.79	3.51
304	1.95	4.14	4.72	5.03
306	2.33	4.09	4.48	5.09
307	2.37	3.70	4.77	5.08
308	1.25	2.66	3.69	4.42
309	1.17	2.38	3.84	4.78
310	0.81	2.06	3.50	4.09
311	0.43	1.47	3.21	4.09
312	0.49	1.08	2.54	3.15
313	0.60	1.46	2.85	3.77
314	1.22	2.46	3.09	4.06
315	0.36	1.47	2.45	3.21
316	0.53	1.67	2.78	3.09
318	0.54	1.12	1.69	2.70
319	0.31	1.46	2.87	3.72

Table A2. (Continued)

Experiment number	Fertilizer treatment, N-P_2O_5, kg/ha			
	0-60	40-60	80-60	120-60
320	0.25	1.34	3.15	4.24
321	0.31	2.31	3.84	4.79
322	1.73	2.08	2.64	2.93
323	0.88	1.95	3.00	4.12
402	1.02	1.86	2.78	2.93
405	1.99	3.31	3.87	4.32
406	0.70	1.88	2.26	2.58
408	1.04	1.66	1.85	1.94
409	2.75	3.74	4.09	4.10
410	2.57	4.06	4.49	4.42
411	2.67	3.01	2.75	3.00
412	1.03	2.63	3.70	3.75
413	1.45	2.62	2.77	3.42
414	0.32	2.03	3.58	4.86
415	1.16	3.23	4.51	5.31
416	1.57	2.98	4.08	5.08
417	0.92	2.39	4.01	5.01
418	1.74	4.07	4.94	5.27
419	1.42	2.97	4.74	6.12
420	1.61	3.30	3.80	4.60
421	0.33	1.30	1.94	2.32
422	1.86	2.93	4.18	4.44
423	4.73	4.93	6.08	6.18
501	2.25	3.55	3.92	4.16
503	4.64	4.83	5.21	5.05
504	3.59	4.31	4.97	4.65
505	1.03	2.91	3.23	3.45
506	2.48	3.69	5.01	5.38
507	3.35	3.86	4.95	5.21
508	1.80	3.02	3.88	4.54
509	1.42	2.19	3.39	3.93
510	0.97	1.74	2.93	4.26
511	0.96	1.86	3.41	4.26
512	0.93	1.81	3.21	4.35
513	1.57	2.31	3.24	3.98
514	1.98	2.35	4.00	4.82
515	1.34	2.35	3.49	4.35
516	1.04	1.93	2.80	3.93

Table A3. Previous crop, planting date of the corn variety, days to silking, and observations of the effects of some factors limiting corn yields

Expt. no.	Previous crop	Planting date	Variety	Days to silking date	Weed competition[a]	Leaf blight damage[a]	Hail damage[a]
202	Fallow	Jun 19	H-230	68	No	L	No
203	Chickpea	19	H-230	87	VS	No	L Jul 24
204	Fallow	20	H-230	78	M	No	L Jul 15
206	Fallow	23	H-230	77	M	VL	No
207	Sorghum	19	H-230	81	No	VL	L Jul 11
208	Corn	19	H-230	69	No	M	L Jul 11
209	Chickpea	22	H-230	75	No	No	No
210	Sorghum	22	H-230	77	L	No	VS Aug 16
211	Fallow	22	H-230	76	L	No	No
212	Corn	22	H-230	71	L	VL	No
213	Chickpea	20	H-230	78	No	VL	L Aug 16
216	Corn	21	H-220	76	No	VL	No
217	Corn	19	H-230	80	No	No	No
218	Chickpea	24	H-220	72	No	No	No
219	Corn	19	H-220	63	No	VL	No
220	Sorghum	19	H-220	73	No	No	No
221	Chickpea	19	H-220	68	M	No	No
222	Sorghum	19	H-230	79	L	No	No
227	Corn	29	H-220	68	No	No	No
228	Corn	28	H-220	71	L	No	No
229	Corn	29	H-220	69	M	No	No
232	Corn	25	H-220	76	No	No	No
301	Corn	20	H-220	75	No	VL	No
302	Fallow	18	H-220	73	VL	VL	No
303	Fallow	8	H-220	73	VL	VL	No
304	Fallow	22	H-220	73	L	VL	No
306	Bean	16	H-220	77	VL	VL	No
307	Corn	16	H-220	75	No	VL	No
308	Corn	17	H-220	83	M	VL	No
309	Corn	9	H-220	71	No	L	No
310	Sorghum	11	H-220	76	VL	VL	L Aug 13
311	Corn	20	H-220	77	L	VL	VL Aug 8
312	Corn	17	H-230	75	No	M	VL Jul 29
313	Sorghum	17	H-230	79	VL	S	VL Sep 17
314	Corn	16	H-230	79	No	VL	No
315	Chickpea	17	H-230	85	S	VL	M Aug 28

[a]VL = very light, L = light, M = moderate, S = severe, and VS = very severe.

Table A3. (Continued)

Expt. no.	Previous crop	Planting date	Variety	Days to silking date	Weed compe- tition	Leaf blight damage	Hail damage
316	Chickpea	Jun 17	H-230	82	M	S	No
318	Corn	19	H-230	73	L	VS	VL Sep 17
319	Chickpea	16	H-230	76	No	S	No
320	Sorghum	15	H-230	74	No	M	Vl Jul 15
321	Corn	16	H-230	79	No	L	VL Jul 15
322	Fallow	10	H-230	76	L	L	L Jul 15
323	Sorghum	12	H-220	75	No	VL	VL Aug 5
402	Corn	4	H-220	77	No	No	L Jul 13
405	Sorghum	17	H-220	76	No	No	L Jul 13
406	Fallow	17	H-220	79	No	No	No
408	Corn	19	H-220	81	L	No	S Aug 18
409	Corn	19	H-220	75	L	No	L Aug 3
410	Fallow	18	H-220	77	L	No	No
411	Corn	12	H-220	77	No	VL	No
412	Sorghum	15	H-220	74	L	VL	No
413	Fallow	17	H-220	72	L	VL	No
414	Sorghum	19	H-220	75	No	L	L Aug 19
415	Corn	20	H-220	75	No	L	No
416	Sorghum	18	H-220	76	No	VL	No
417	Sorghum	18	H-220	76	No	VL	No
418	Sorghum	13	H-220	75	No	L	No
419	Corn	13	H-220	79	L	VL	No
420	Chickpea	15	H-220	75	No	VL	No
421	Sorghum	16	H-220	82	No	VL	No
422	Corn	15	H-220	77	No	VL	No
423	Corn	11	H-220	77	L	VL	No
501	Corn	23	H-220	83	No	No	No
503	Corn	Jul 7	H-220	75	No	No	L Aug 15
504	Chickpea	7	H-220	77	No	No	No
505	Onion	6	H-220	79	L	No	L Sep 10
506	Sorghum	Jun 22	H-220	79	No	VL	No
507	Fallow	23	H-220	77	L	VL	No
508	Corn	19	H-220	78	No	L	No
509	Corn	19	H-220	80	No	L	No
510	Corn	19	H-220	79	No	L	No
511	Corn	19	H-220	80	No	L	No
512	Corn	19	H-220	81	No	L	L Sep 21
513	Fallow	19	H-220	80	No	L	L Sep 21
514	Sorghum	19	H-220	80	No	L	No
515	Fallow	18	H-220	75	No	L	No
516	Sorghum	19	H-220	81	L	L	No

Table A4. Single values for the three approaches used to characterize weather for light-textured soils

Experiment number	Moisture stress index (MS7)	Rainfall 80-day period (mm)	Wilting plant index 70-day period (days)
211	0.0	544	6
227	0.5	424	10
232	1.1	310	21
301	27.4	229	37
302	4.4	358	16
303	5.9	430	12
304	1.3	404	10
306	0.6	333	0
307	0.3	423	0
402	39.5	179	31
405	15.7	312	20
406	19.5	363	22
408	2.5	401	21
409	18.5	359	17
410	21.2	377	16
411	31.6	258	19
412	11.4	360	11
413	2.5	376	6
501	0.0	521	0
503	0.0	537	0
504	0.0	429	0
505	3.8	473	0
506	0.0	580	0
507	0.1	512	0
Mean	8.6	396	11.5
Std. dev.	11.5	99	10.6
C.V. (%)	134	25	92
Range	0-39.5	179-580	0-37

Table A5. Simulation of optimal nitrogen rates for a 31-year period using the final yield prediction model in four locations of the light-textured soils area

Year	Silao, Gto.	Aldama, Gto.	Irapuato, Gto.	Abasolo, Gto.
	-------Nitrogen optimal	rate, kg/ha----------		
1945	-	-	56	-
1946	-	-	76	-
1947	-	-	76	-
1949	50	54	70	75
1950	61	47	56	74
1951	63	78	77	78
1952	72	68	72	74
1953	63	73	71	73
1954	42	61	69	68
1955	75	78	78	79
1956	60	76	61	69
1957	53	76	51	61
1958	76	98	-	114
1959	47	118	83	83
1960	87	94	89	66
1961	33	44	47	56
1962	62	69	76	71
1963	59	56	76	72
1964	69	94	88	73
1965	84	96	92	111
1966	68	59	66	77
1967	94	99	103	108
1968	72	80	71	57
1969	48	46	65	76
1970	73	90	100	96
1971	108	89	-	85
1972	73	56	51	76
1973	90	82	94	94
1974	69	67	61	66
1975	90	79	73	89
1976	107	94	57	82
1977	74	66	82	64
1978	72	62	88	74
1979	72	73	-	81
Mean	69.9	75.0	73.4	78.3
Std. dev.	17.3	17.9	14.5	14.3
C.V. (%)	24.8	23.9	19.8	18.3
Range	33-108	44-118	47-103	56-114

Table A6. Corn yield simulation (ton/ha) for a 31-year period using the final yield prediction model at three levels of plant-available water capacity (PAWC) for four locations

	PAWC (mm)			PAWC (mm)		
Year	72	144	216	72	144	216
	Silao, Gto.			Aldama, Gto.		
1949	2.03	2.71	3.39	2.15	2.83	3.51
1950	2.39	3.07	3.75	1.96	2.64	3.32
1951	2.44	3.12	3.80	2.93	3.61	4.28
1952	2.72	3.40	4.08	2.61	3.29	3.97
1953	2.44	3.12	3.80	2.77	3.45	4.13
1954	1.80	2.48	3.15	2.37	3.05	3.73
1955	2.82	3.50	4.18	2.92	3.60	4.28
1956	2.34	3.02	3.70	2.87	3.55	4.22
1957	2.12	2.80	3.48	2.84	3.52	4.20
1958	2.84	3.52	4.20	3.54	4.22	4.90
1959	1.95	2.63	3.31	4.15	4.83	5.51
1960	3.18	3.86	4.54	3.43	4.11	4.78
1961	1.52	2.20	2.88	1.87	2.55	3.23
1962	2.42	3.09	3.77	2.62	3.30	3.98
1963	2.32	3.00	3.68	2.24	2.92	3.60
1964	2.62	3.30	3.98	3.40	4.08	4.76
1965	3.09	3.77	4.45	3.47	4.16	4.89
1966	2.59	3.27	3.95	2.32	3.00	3.68
1967	3.39	4.07	4.75	3.57	4.25	4.93
1968	2.72	3.40	4.08	2.97	3.65	4.33
1969	1.97	2.65	3.33	1.92	2.60	3.27
1970	2.74	3.42	4.10	3.30	3.98	4.66
1971	3.81	4.49	5.17	3.27	3.95	4.63
1972	2.74	3.42	4.10	2.22	2.90	3.58
1973	3.28	3.96	4.64	3.04	3.72	4.39
1974	2.64	3.32	4.00	2.56	3.24	3.92
1975	3.27	3.95	4.62	2.95	3.63	4.31
1976	3.81	4.49	5.16	3.41	4.09	4.76
1977	2.77	3.45	4.13	2.55	3.22	3.91
1978	2.71	3.39	4.07	2.41	3.09	3.77
1979	2.69	3.37	4.05	2.76	3.44	4.12
Mean	2.65	3.33	4.01	2.82	3.50	4.18
Std. dev.	.537	.537	.537	.558	.558	.558
C.V. (%)	20.2	16.1	13.4	19.8	15.9	13.4
Range	1.52-3.82	2.20-4.50	2.88-5.17	1.87-4.15	2.55-4.83	3.22-5.51

Table A6. (Continued)

Year	PAWC (mm) 73	144	216	PAWC (mm) 72	144	216
	Irapuato, Gto.			Abasolo, Gto.		
1945	2.23	2.91	3.59	-	-	-
1946	2.89	3.56	4.24	-	-	-
1947	2.89	3.56	4.24	-	-	-
1949	2.68	3.36	4.04	2.88	3.56	4.24
1950	2.22	2.90	3.58	2.84	3.53	4.20
1951	2.92	3.60	4.28	2.78	3.66	4.33
1952	2.75	3.43	4.11	2.87	3.55	4.23
1953	2.74	3.42	4.09	2.83	3.51	4.19
1954	2.68	3.36	4.03	2.64	3.32	4.00
1955	2.97	3.65	4.32	3.01	3.69	4.37
1956	2.41	3.09	3.77	2.68	3.36	4.04
1957	2.09	2.76	3.45	2.40	3.08	3.76
1958	-	-	-	4.20	4.89	5.56
1959	3.10	3.78	4.46	3.17	3.85	4.53
1960	3.32	4.00	4.67	2.58	3.27	3.95
1961	1.93	2.61	3.29	2.23	2.91	3.59
1962	2.88	3.56	4.24	2.94	3.62	4.30
1963	2.90	3.58	4.25	2.77	3.45	4.13
1964	3.29	3.97	4.64	2.83	3.52	4.19
1965	3.42	4.09	4.77	4.11	4.79	5.47
1966	2.56	3.23	3.92	2.97	3.65	4.33
1967	3.76	4.44	5.12	4.01	4.70	5.38
1968	2.73	3.40	4.08	2.29	2.97	3.64
1969	2.54	3.22	3.89	2.91	3.59	4.27
1970	3.67	4.35	5.02	3.60	4.28	4.95
1971	-	-	-	3.24	3.92	4.60
1972	2.06	2.74	3.42	2.91	3.59	4.27
1973	3.48	4.17	4.85	3.54	4.22	4.90
1974	2.40	3.08	3.76	2.58	3.26	3.95
1975	2.80	3.48	4.16	3.36	4.03	4.72
1976	2.27	2.95	3.63	3.13	3.81	4.49
1977	3.08	3.77	4.44	2.52	3.19	3.87
1978	3.29	3.97	4.65	2.87	3.55	4.22
1979	-	-	-	3.10	3.79	4.46
Mean	2.80	3.48	4.16	3.00	3.68	4.36
Std. dev.	.474	.474	.474	.486	.486	.486
C.V. (%)	16.9	13.6	11.4	16.2	13.2	11.1
Range	1.93-3.76	2.61-4.44	3.29-5.12	2.23-4.21	2.91-4.89	3.69-5.56

Table A7. Excess moisture, moisture stress and rainfall values for the weather approaches used in clay-soils area

Experiment number	Excess moisture index (EM54)	Moisture stress index (MS54)	Rainfall 48-day period (R48), mm	Rainfall 30-day period (R30), mm
202	23	4	213	269
203	33	7	265	160
204	22	0	289	133
206	24	1	201	263
207	19	0	264	220
208	28	0	258	192
209	45	0	261	218
210	51	0	367	136
212	53	0	316	312
213	32	0	260	307
216	28	0	171	219
217	22	0	259	206
218	17	0	188	211
219	28	0	217	183
220	18	3	241	205
221	21	0	241	218
222	29	13	196	210
228	24	24	183	245
229	16	25	183	245
308	35	6	302	134
309	43	0	365	148
310	49	0	469	107
311	48	0	571	141
312	46	0	605	131
313	40	0	605	118
314	41	0	565	89
315	47	0	415	104
316	45	0	360	144
318	42	0	498	72
319	52	0	403	89
320	52	0	480	116
321	50	0	456	86
322	54	0	500	54
323	43	0	471	99

Table A7. (Continued)

Experiment number	Excess moisture index (EM54)	Moisture stress index (MS54)	Rainfall 48-day period (R48), mm	Rainfall 30-day period (R30), mm
414	31	0	181	162
415	30	33	245	168
416	46	1	200	175
417	26	0	200	175
418	27	0	222	235
419	36	0	250	242
420	47	0	198	114
421	36	0	157	129
422	31	0	147	117
423	20	0	124	142
508	40	2	398	120
509	52	0	431	171
510	44	0	418	189
511	37	0	438	159
512	42	0	433	158
513	49	0	437	129
514	48	0	452	206
515	54	0	329	86
516	54	0	351	145
Mean	37.2	2.2	325	166
Std. dev.	11.6	6.6	130	59
C.V. (%)	31.2	300	40.0	35.5
Range	16-54	0-33	124-605	54-312

Table A8. Simulation of corn yields (ton/ha) at two rooting depths for a 26-, 27- and 28-year period, using the final yield prediction model for Tototlan, Atotonilco and Ayo El Chico, respectively

	Rooting depth (cm)					
Year	60	120	60	120	60	120
	Tototlan, Jal.		Atotonilco, Jal.		Ayo El Chico, Jal.	
1950	-	-	-	-	4.81	5.45
1951	4.36	5.00	4.74	5.39	4.08	4.72
1952	4.23	4.87	4.38	5.03	4.44	5.09
1953	3.58	4.22	4.28	4.93	4.33	4.97
1954	4.37	5.01	4.04	4.69	4.14	4.79
1955	4.23	4.88	3.78	4.43	3.99	4.64
1956	4.08	4.73	4.36	5.01	3.94	4.58
1957	4.54	5.19	4.55	5.20	4.77	5.41
1958	4.84	5.49	4.37	5.01	4.75	5.39
1959	4.20	4.85	3.87	4.52	4.65	5.30
1960	3.94	4.59	4.19	4.83	3.70	4.34
1961	4.57	5.21	4.00	4.65	4.14	4.79
1962	4.29	4.94	4.62	5.27	4.80	5.45
1963	4.40	5.05	-	-	3.51	4.16
1964	4.74	5.39	4.60	5.24	4.36	5.00
1965	4.59	5.24	4.00	4.64	4.12	4.77
1966	4.08	4.73	4.43	5.08	4.17	4.81
1967	-	-	5.52	6.16	5.36	6.01
1968	4.27	4.92	4.26	4.90	4.10	4.74
1969	-	-	4.75	5.39	4.90	5.54
1970	3.83	4.48	3.88	4.53	4.29	4.94
1971	4.48	5.12	4.73	5.38	4.55	5.19
1972	4.43	5.08	4.72	5.36	4.36	5.01
1973	3.79	4.44	3.56	4.20	3.37	4.02
1974	4.03	4.68	3.87	4.52	4.41	5.05
1975	4.41	5.05	3.42	4.07	3.92	4.57
1976	3.62	4.27	3.22	3.87	3.32	3.97
1977	4.71	5.36	5.00	5.65	-	-
1978	4.37	5.02	4.38	5.03	4.48	5.13
Mean	4.27	4.92	4.28	4.92	4.28	4.92
Std. dev	.329	.329	.503	.503	.472	.472
C.V. (%)	7.7	6.7	11.7	10.2	11.0	9.6
Range	3.58- 4.84	4.22- 5.49	3.22- 5.52	3.87- 6.16	3.32- 5.36	3.97- 6.01

Table A9. Simulation of corn yields (ton/ha) at two rooting depths for a 32-, 19- and 31-year period, using the final yield prediction model for El Salto, Penjamo and Abasolo, respectively, for clay-soils area

	Rooting depth (cm)					
Year	60	120	60	120	60	120
	El Salto, Mich.		Penjamo, Gto.		Abasolo, Gto.	
1944	-	-	4.12	4.77	-	-
1945	-	-	3.94	4.58	-	-
1946	-	-	4.57	5.21	-	-
1947	-	-	5.36	6.00	-	-
1948	3.47	4.11	4.18	4.83	-	-
1949	4.58	5.22	4.07	4.71	4.29	4.94
1950	4.48	5.13	5.09	5.73	4.34	4.98
1951	3.90	4.54	4.38	5.03	4.69	5.33
1952	4.58	5.23	4.55	5.20	4.40	5.05
1953	4.61	5.26	-	-	4.59	5.23
1954	4.78	5.42	-	-	4.37	5.01
1955	4.77	5.41	-	-	4.30	4.94
1956	4.13	4.78	4.38	5.03	4.17	4.82
1957	4.78	5.43	4.25	4.90	4.51	5.16
1958	4.49	5.13	4.75	5.39	4.72	5.37
1959	4.19	4.83	4.24	4.89	4.36	5.01
1960	4.85	5.49	4.20	4.85	4.25	4.90
1961	4.25	4.90	4.22	4.86	4.20	4.85
1962	4.70	5.34	4.79	5.44	4.86	5.51
1963	4.11	4.76	3.93	4.58	4.14	4.79
1964	4.40	5.05	4.32	4.97	4.83	5.48
1965	4.22	4.86	-	-	3.85	4.49
1966	4.44	5.09	4.64	5.29	4.56	5.21
1967	5.01	5.65	-	-	4.62	5.26
1968	4.62	5.26	-	-	4.38	5.02
1969	5.10	5.75	-	-	4.54	5.19
1970	4.05	4.70	-	-	4.65	5.30
1971	4.10	4.75	-	-	4.24	4.89
1972	4.27	4.92	-	-	4.56	5.20
1973	3.52	4.17	-	-	3.51	4.16
1974	3.70	4.35	-	-	4.35	5.00

Table A9. (Continued)

	Rooting depth (cm)					
Year	60	120	60	120	60	120
	El Salto, Mich.		Penjamo, Gto.		Abasolo, Gto.	
1975	4.98	5.62	-	-	3.90	4.55
1976	4.04	4.68	-	-	3.66	4.31
1977	4.96	5.60	-	-	4.68	5.33
1978	3.93	4.57	-	-	4.39	5.04
1979	4.54	5.18	-	-	4.32	4.97
Mean	4.39	5.04	4.42	5.07	4.36	5.01
Std.dev.	.426	.426	.377	.377	.315	.315
C.V. (%)	9.7	8.5	8.5	7.4	7.2	6.3
Range	3.47- 5.10	4.11- 5.75	3.93- 5.36	4.58- 6.00	3.51- 4.87	4.16- 5.51