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FOR IOWA AND ILLINOIS.

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GRADUATE COLLEGE

ANALYSIS OF CROP CALENDAR CORN YIELD MODELS FOR IOWA AND ILLINOIS

A DISSERTATION

SUBMITTED TO THE GRADUATE FACULTY

in partial fulfillment of the requirements for the

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DOCTOR OF PHILOSOPHY

BY

VASUDEVA RAO ACHUTUNI

Norman, Oklahoma

1978

ANALYSIS OF CROP CALENDAR CORN YIELD
MODELS FOR IOWA AND ILLINOIS

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ABSTRACT

ANALYSIS OF CROP CALENDAR CORN YIELD MODELS FOR IOWA AND ILLINOIS

Crop calendar based corn yield models have been developed for Iowa and Illinois at the state and macro-CRD levels. Applied nitrogen fertilizer accounts for the technological input to the models. Average weekly precipitation and temperature data form the primary weather input, and derived agro-meteorological variables constitute the secondary weather input to the models.

The stepwise regression procedure was used to select the significant variables in each model. A multiple linear regression model was also fitted using physiological reasoning in selecting the variables. Truncated models have also been developed in order to assess the operational usefulness of the stepwise procedure and multiple regression analysis models.

Standard jackknife and bootstrap techniques were used in testing the individual models. An independent test was made on each model using the 1974-1976 data. Detailed sensitivity analyses were made by varying the model coefficients and weather inputs over their range of uncertainty. Some model scenarios were also created to study plausible situations such as drought.

In spite of the data limitations, the models developed in this study were found to be reasonably sensitive to the technological changes and uncertainties in the weather. Large positive and negative deviations in yield can still occur as a result of the interaction between weather and technology. The individual state and macro-CRD models developed were found to be reasonably stable over the period tested. The use of a phenological time scale in studying climate-yield relationships was found to be invaluable. Finally, models based on applied nitrogen fertilizer require that the fertilizer data be reported as accurately as possible, otherwise large residual errors are likely to occur.

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CHAPTER I

INTRODUCTION

The United States produces nearly 58 percent of the world's corn. Approximately 90 percent of the United States corn is utilized within the country for feeding animals (Watson, 1977). Two-thirds of this corn is produced in the Corn Belt, which includes the states of Ohio, Indiana, Illinois, Iowa and Missouri. Here the soils and climatic conditions are very favorable for the production of corn (Shrader and Pierre, 1966). The Corn Belt falls within Trewartha's temperate, continental-climate zone which is characterized by four to seven months in a year with average temperature over 50°F and the warmest months temperature exceeding 71.96°F (Shaw, 1977).

The Corn Belt experienced somewhat favorable weather for the production of corn from 1956 through 1973 (McQuigg, 1975; Thompson, 1975). The steady increases in yield over that period were attributed by many to improved technology. The drought of 1974 drastically reduced corn yields in Iowa and Illinois, even though the farmers had applied large amounts of fertilizer that season. Increased fertilizer usage, effective weed and pest control, improved and timely farm practices and better seed varieties are resulting in high yields whenever the weather is favorable for the growth and development of the crop. However, weather disasters are still capable of offsetting the benefits of technology in corn production.

According to McQuigg (1975), the three major sources of variability in yield are the changing technology, meteorological variability and random events. The significant increases in corn yields since 1955 can be attributed to increased fertilizer usage, that is, change in technology. The 1974 growing season was characterized by excessively wet weather around planting, cooler and wetter than normal conditions in late July, and a series of early frosts in September. The subsequent yield reductions were due to these meteorological aberrations which demonstrate the meteorological variability possible. The southern corn leaf blight epidemic of 1970 is an excellent example of the extent of yield reductions that may be attributed to random events unexplained by weather or the current understanding of technology. It is extremely difficult to model such random events; one can only make "mid-course corrections" to the model with a posteriori knowledge.

Corn yield models are of economic importance as they provide yield estimates during the current growing season. Farmers can use this information to regulate their existing stocks. Based on the trend in feed and meat prices, livestock feeders can regulate the number of animals on concentrate feed.

A. Relevance of This Study

Adverse weather events such as those that occurred during 1972 in the major grain producing regions of the world can have drastic effects on the world grain reserves. Several countries in the world have started developing weather related crop yield models on an operational basis (Baier, 1977). These models provide a means by which past and present weather information can be combined with technological input in estimating crop yields during the course of the current growing season.

In this country corn is essentially used as feed for hogs, cattle and poultry; the remaining surplus is exported to other countries. Crop failures such as those in 1970 and 1974 will affect the farmer, consumer and government alike. The need for monitoring corn yields during the growing season is apparent. The present study aims at developing regional and state level corn yield models based on weather, phenology and technology. Results from these models are applicable only to large areas and not individual farms. On an operational basis, such models may provide valuable information to the researcher as well as the policy maker reasonably early in the growing season.

Besides weather, there are several economic factors that control corn production. The supply-demand concept is described briefly.

The acreage of corn planted by farmers depends on the price they received for the previous crop and also on the projected market value for the current year's crop. According to the Feed Situation (USDA, Economics, Statistics and Cooperatives Service, 1978), livestock feeders make their decisions on their concentrate feeding operations during the October-September feeding year. Feed costs influence the number of farrowings and the number of cattle placed on feed. Poultry feeders respond more quickly to fluctuating market conditions. This year the hog producers decided to curb the expansion in farrowings because of cold weather related disease problems. The report also forecasts United States corn exports for 1977/1978 at a record 1,750 million bushels. Commitments to the U.S.S.R. are 387 million bushels as of late April.

Crop prospects within the country and abroad have a definite impact on the prices received by farmers for every bushel of corn. Adequate supplies, relatively little corn held under the government loan program, and favorable weather at home and abroad reduce the market value of corn whereas, inadequate supplies accompanied by a good demand guarantee a decent profit.

B. The Yield Estimation Problem

Ideally, it is desirable to model the growth and development of individual corn plants giving due considerations to the physical, chemical and physiological mechanisms underlying these processes. By using such crop-growth simulation models, plant responses to environmental conditions and technological inputs such as fertilizer, pesticides, herbicides and irrigation can be studied in detail. The corn model developed by Lemon et al. (1971) is one such example. These crop-growth simulation models require a massive experimental set up combined with interdisciplinary team work. In view of the detailed information needed to run such models and the enormous computational time involved, the use of crop-growth simulation models is limited to experimental research.

At present, crop yields are generally reported at the state or crop reporting district (CRD) levels. Fertilizer application rates and often phenological data are available only at the state level. And so operational crop yield models are usually developed for such large areas of production. The meteorological data required to run these models are collected from weather stations located within each CRD on either a daily, weekly or monthly basis.

In the statistical approach to crop yield modeling several variables (representing weather, cultural practices, soil-characteristics, fertilizer usage or a time trend) are related to crop yields by means of multiple linear regression techniques. Baier (1977) is of the opinion that the coefficients in such empirical models and the validity of the estimates depends to a large extent on the representativeness of the input data and experimental design of the model. If the soil, climate and cropping practices are reasonably homogenous over the area covered by the model, then the coefficients and estimates have a practical significance for predicting crop yields.

C. Scope of this Research

The present effort aims at developing corn yield models for Iowa and Illinois at the state and aggregated crop reporting district (CRD) levels. A non-linear yield trend or the nitrogen fertilizer application rate will constitute the technological input. Average weekly precipitation and temperature data form the primary weather input, and derived variables such as weekly soil moisture, number of days in a week exceeding 90°F, will include some of the secondary weather input to be tested. Average weekly values for all the weather variables are computed based on a "crop calendar" rather than a fixed one, the advantage being that the weather effects will be captured at observed or predicted stages of crop development instead of at fixed intervals. A delay in planting will affect adversely a fixed time model because the "crop time" and the "model time" will be out of phase.

In this study corn yield models are developed using both the stepwise regression procedure and the multiple linear regression analysis technique. The stepwise procedure picks the "best" set of predictor variables for each model, using the given data series. As the existing data set covers a period of only 24 years, some of the variables selected by the stepwise procedure may not be physiologically significant for the crop. In an effort to develop "physiologically sound" models, the multiple linear regression approach has been taken. In this approach, the model variables are selected a priori by the modeler using physiological reasoning and known climate-yield relationships.

Truncated models use the weather and phenological information up to and including the time of truncation. Such truncated models enable the modeler to predict yield at different stages in the growing season. The models developed in this study include two such truncations, the first at planting and the second at silking.

Standard jackknife and bootstrap tests are used in testing the individual models and studying the stability of their coefficients. The 1974-1976 data set is being used to perform independent tests on the individual models.

Sensitivity analysis procedures developed earlier by Eddy (1978) are used in studying model sensitivity. A detailed sensitivity analysis is made by varying the model coefficients and weather inputs over their range of uncertainty. Also, some model scenarios are created to study certain plausible situations such as droughts.

Results from this study are applicable only to large areas such as a CRD or a state. The models assume horizontal homogenity in soil types, soil factors, phenology and fertilizer usage. In spite of the data limitations, the models developed in this study are reasonably sensitive to changes in technology and uncertainties in the weather. Results from this study are promising enough to consider making some of these models operational. The models are easy to operate and consume very little computer time once the data sets are ready. As new areas are progressively included, the model coefficients have to be recomputed. It can be inferred that the universality of crop-yield models is a problem which requires further study.

CHAPTER II

FACTORS TO BE CONSIDERED IN THE PRODUCTION OF CORN

A. Stages of Corn Development and Climatic Requirement

Hanway (1971) divided the corn plant development into ten stages ranging from emergence to physiological maturity. Figure 1 illustrates his general scheme, the average week for the occurrence of corresponding stages in Iowa and Illinois have also been incorporated. Shaw (1977) aggregated these ten stages into seven categories based on physiological and climatic requirements.

According to Hanway (1971) growth stages prior to silking can be identified by the number of leaves that have emerged, and also by length of the internode. Stages of growth after silking are identified by the development of the kernels. Weather effects at various stages of plant growth and development are considered below.

A.1. Prior to Planting

The weather prior to planting influences corn yields considerably. Freezing weather in the winter improves soil tilth and kills the hibernating larva of corn borers (Dicke, 1977), and thawing of soil in the spring helps to reduce soil clods. Soil moisture reserves in spring

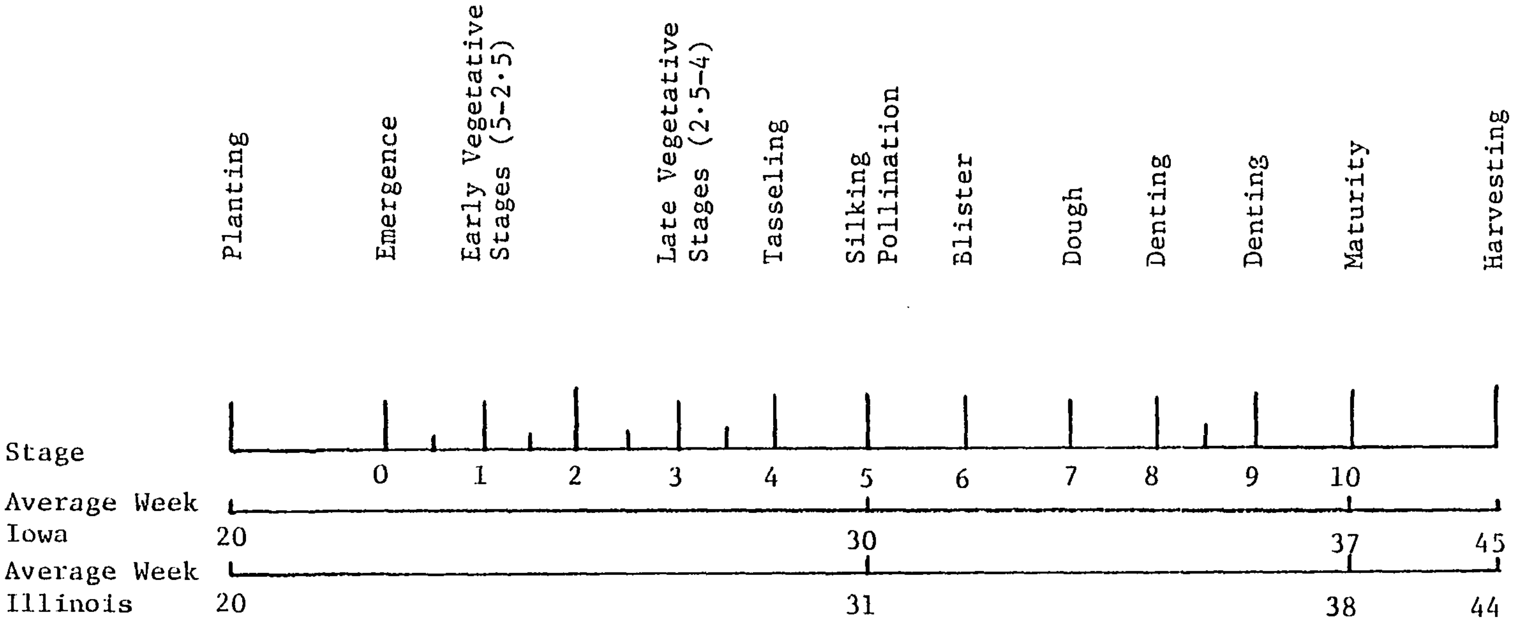

Figure 1. Phenological Stages for Corn Based on Hanway's Time Scale (Hanway, 1971). The Average Weeks for Planting, Silking, Maturity and Harvesting in Iowa and Illinois are Shown for Comparison.

depend a lot on the precipitation during winter. In spring farmers base their nitrogen fertilizer application rates on the soil moisture levels prior to planting. Adequate moisture reserves encourage farmers to increase the rate of application of nitrogen.

Excessive precipitation prior to planting delays planting operations, whereas dry weather ensures early planting. Efficient weed control methods and improved seed varieties are prompting farmers to plant early in the season. High yielding late maturing varieties can then be safely planted. A delay in planting will force the farmer to plant early maturing varieties with lower yields.

Zuber (1968) found that April 20 and May 10 were optimum planting dates for corn in Missouri. The late maturing varieties gave the highest yields at the earlier planting dates, whereas the early maturity groups yielded relatively better at the later planting dates. Also the earlier plantings had less root rot and stalk lodging. Pendleton and Egli (1969) noticed yield reductions when planting was delayed beyond April 30 in Illinois. Marley and Ayers (1972) found that all the three varieties they tested exhibited a general reduction in yield with delayed planting. The planting to emergence period also decreased for all varieties as planting was delayed.

A.2. Planting to Emergence

The process of germination involves the absorption of water and initiation of growth in the seed. Temperature, light and soil moisture conditions control this process (Bidwell, 1974). Shaw (1977) says that corn germinates best above 50°F. The rapidity of germination increases with soil moisture up to 80 percent of saturation, and then drops due to lack of oxygen. Below 10 percent of saturation germination ceases due to lack of water. Alessi and Power (1971) claim that emergence is delayed by one day whenever the depth of seed placement is increased by an inch. According to Hanway (1971), under warm, moist conditions emergence takes place in four to five days, cool, dry conditions may delay it by two weeks or longer.

Cool, wet weather after planting favors the development of seed rot and seedling blight (Ullstrup, 1977). The selection of disease resistant hybrids is very important under such conditions.

A.3. Early Vegetative Stage (Stages 0.5 to 3.0)

After emergence the growing point of the plant is still below the ground surface, therefore, late freezes during stages 0.5 to 1.0 will not kill the plant. By the time stage 1.5 is reached, the nodal roots are well distributed in the soil and the plant begins to absorb nutrients from the soil. This is also the time when rootworms may be feeding on the nodal roots.

Stages 2.0 to 3.0 of the early vegetative stage are characterized by rapid leaf development and stem elongation. Therefore, a nutrient stress during this period can substantially reduce leaf growth. The tassel (staminate flowers) and ears (pistillate flowers) also begin to develop rapidly by stage 2.0. Flooding of fields during the early vegetative stage causes oxygen deficiency and the plants may eventually die. The corn borer eggs located in the tassel and ears begin to hatch during this time; therefore, chemical treatment may be necessary.

Thompson (1963) observed that with normal June rainfall in the Corn Belt, the optimum June temperatures ranged from 69.8 to 73.4°F.

Correlations between yield and June temperature or precipitation were low. Denmead and Shaw (1960) found that reductions in yield due to moisture stress early in the vegetative stage amounted to about 25 percent. Yield losses were the result of a reduction in the photosynthetic (leaf) area.

A.4. Late Vegetative Stage (Stages 3.0 to 4.0)

This stage occurs in the latter part of July prior to silking. The tassel is near full size and silks from the base of the ears are slowly developing. Moisture stress nutrient deficiency, during the late vegetative stage, increase in intensity from the top to the bottom of the plant. And silking is generally delayed, as a result of moisture stress and nutrient deficiency (Hanway, 1971).

Thompson (1969) studied weather-corn yield relationships in the Corn Belt. He found a negative correlation between June rainfall and corn yields. Below normal July precipitation was detrimental to yield. He considered 3.6 inches of precipitation to be normal, the yields began to level off with about twice the normal July rainfall.

Denmead and Shaw (1960) reported that moisture stress in the late vegetative stage can reduce yield by 25 percent. According to Shaw (1977) the reduction in yield was partly due to a nutrient deficiency. Classen and Shaw (1970a) observed 15 to 17 percent reductions in the total vegetative dry matter production when stress occurred about three weeks before silking.

A.5. Tasseling, Silking and Pollination (Stages 4.0 to 5.0)

This period is very critical to the corn plant. Tassel emergence is completed by stage 4.0 and silking by stage 5.0. A moisture stress or nutrient deficiency will delay silking to a time when most of the pollen has already been shed and will result in unfilled kernels at the tip of the ears. Also, maximum temperatures above 90°F around tasseling and pollination speed up the reproductive process leading to higher rates of kernel abortion (Shaw, 1977).

Thompson (1969) observed that above normal July rainfall and slightly below normal July and August temperatures were associated with highest yields. Classen and Shaw (1970b) found that moisture stress at 6 percent silking reduced yield only 3 percent per day, whereas, at 75 percent silking yield reductions of up to 7 percent per day were common. An added nutrient stress at silking reduced yields by an additional 6 percent per day. In an earlier study Robins and Domingo (1953) observed significant yield reductions when soil moisture was depleted to the wilting point four weeks after tasseling. After maturity, the soil moisture was not so critical.

Shaw et al. (1958) found that water use by corn averaged 0.10 in/day during April 15 through June 15, and 0.18 in/day for the June 15 through August 15 period. Denmead and Shaw (1959) observed that the ratio of evapotranspiration from corn to pan-evaporation reached a maximum during the mid-July to mid-August period and decreased, both before and after this period. Corsi and Shaw (1971) tested four different moisture stress indices that incorporated the degree of stress for each day. Shaw (1974) developed a weighted moisture stress index for Iowa. Stress at various stages of crop development affects yields differently, a weighting system was developed for each of the five-day periods in the growing season to incorporate this non-linear relationship. Runge and

Benci (1975) considered the period six weeks before silking to four weeks after in estimating corn yields.

Sullivan et al. (1975) investigated water loss from corn and sorghum plants. They found that corn stomata closed earlier under less moisture stress than sorghum stomates, indicating that corn was less effective in retarding further water loss once the stomates were closed. They also found that heat tolerant genotypes of corn and sorghum were able to photosynthesize at a higher rate than the less tolerant ones, when subjected to high temperatures around flowering.

A.6. Fertilization to Physiological Maturity (Stages 6.0 to 10.0)

The blister stage (stage 6) is characterized by a rapid increase in dry weight that will continue till stage 9. Translocation of nitrogen and phosphorus from the older leaves to the ears is rapid. During the dough stage (stage 7) the kernels grow rapidly, starch begins to accumulate in the endosperm. Unfavorable conditions or a phosphorus deficiency will result in unfilled and chaffy ears. Stages 8 and 9 are called the dent stages. Dry matter accumulation proceeds at a lower rate and will cease by the time physiological maturity (stage 10). The grains will continue to lose moisture after this stage (Hanway, 1971).

Classen and Shaw (1970b) observed yield reductions between 4 to 7 percent, due to moisture stress around ear filling. Others (Denmeand and Shaw, 1960; Robins and Domingo, 1953) observed smaller yield reductions.

Thompson (1969) found that slightly below normal August temperatures were beneficial for yields in the Corn Belt. Bondavalli et al.

(1970) observed that temperature during the second half of May and precipitation during the first half of August affected corn yield significantly. According to Shaw (1977) above normal August rainfall is beneficial to corn yields only if it happens to be a dry year. According to him in a dry year, the late maturing varieties of corn yield less if September is dry. In a wet year soil moisture reserves for the next season are increased but harvesting may be delayed.

Neild and Seely (1977) used growing degree days between 50 to 86°F to predict corn and sorghum development. They found a close correlation between growing degree days and crop development. The difference in growing degree day requirements between the varieties increased with crop development. As seeds are generally sold on a maturity rating, their approach can be used to predict the time of maturity.

In summary, the various stages in the growth and development of corn respond differently to moisture, temperature and nutrient stress in relationship to yield. An early planting enables the crop to complete silking before stress develops, also high yielding late maturing varieties can be planted. Moisture stress around silking reduces the yield more than stress during the vegetative or grain filling stages. Dry weather after maturity favors the drying of the grain and enables an early harvest. Table 1 shows the important climate-yield relationships for corn at various stages of growth and development.

B. Diseases of Corn

Estimates of annual disease losses in corn range from two to seven percent in the U.S.A. (Ullstrup, 1977). It was generally believed that diseases of corn seldom spread in severe proportions. The southern

STAGE	CLIMATIC REQUIREMENT	CLIMATIC FACTORS DETRIMENTAL TO YIELD
Preplant	A cold winter with moderate snowfall.	A mild winter permits overwintering.
Planting	Dry weather favors early planting.	Cold and wet--delayed planting.
PLTG-0.0	Warm and moist--early emergence.	Warm and dry--late emergence.
0.0-4.0	Slight moisture stress improves root system.	Flooding kills plants. Severe moisture stress reduces yield by 25%.
4.0-5.0	Normal Jun-Jul temperatures and adequate soil moisture--timely pollination.	Moisture stress delays silking. Hot, dry weather causes poor pollination and seed set.
5.0-6.0	Normal temperatures and adequate soil moisture aid grain filling process.	Loss of leaves due to hail results in unfilled ears.
6.0-9.0	Normal temperatures and adequate soil moisture aid grain filling process.	Hot and dry weather reduces yield by 4 to 7%.
9.0-10.0	Warm and dry weather ensures quick drying of ears.	Cool and wet conditions delay drying process.
Harvest	Dry weather enables an early harvest.	Frequent rains delay harvesting.

Table 1. Some Important Climate-Yield Relationships for Corn in Iowa and Illinois

corn leaf blight epidemic in 1970, however, changed this popular notion. This resulted in a closer monitoring of the diseases of corn and their potential effects.

Diseases may affect corn production in several ways. Seedling diseases reduce the stand, but the healthier plants compensate stand reductions by using the additional amounts of nutrients and soil moisture. On the other hand, leaf diseases reduce the photosynthetic area thereby lowering the yield. Stalk rots and root rots cause lodging, such corn is difficult to harvest. Ear rots reduce the quality of the grain.

For a disease to develop the environment should be favorable, a disease inducing pathogen should be present, and the host should be susceptible to the disease. At times the presence of a vector or agent is necessary for transporting the disease. According to Ullstrup (1977) losses due to disease may be minimized in several ways. Selection of resistant hybrids is an effective means. The use of fungicides is limited due to extensive culture of the crop and high cost of such operations. Cultural practices such as maintaining a well balanced soil fertility, crop rotation and destruction of refuse harboring pathogens of corn diseases are recommended.

B.1. Seed Rot and Seedling Blights

Seed rot causes a complete decay of the seed before or around germination. Seedling blight may occur prior to, or after, emergence. Some of the below ground symptoms include brown water soaked lesions on the roots, rotting of root tips or brown lesions on the mesocotyl. Mesocotyl infection by Pennicilium oxalicum thom causes progressive wilting and subsequent death beginning at the tip of the leaves. Sunken lesions on the mesocotyl follow infection by Gibberella zeae (Schw.) Petch. Stunting is associated with most seedling blights (Ullstrup, 1977).

Seed rot and seedling blight can be controlled by treating the seed with fungicides. Avoidance of mechanical damage to seed, use of well matured seed; storage of seed at the right temperature and humidity; and planting under temperatures favorable for germination are some of the possible preventive cultural practices.

B.2. Stalk and Root Rots

Stalk rot fungi are weak parasites that invade the host when it is under stress of the aging process, usually several weeks after silking. High levels of nitrogen combined with low amounts of potassium favor premature dying, stalk breakage and stalk rotting. According to Ullstrup (1977) there is evidence suggesting potassium chloride is superior to other forms of potassium in reducing the severity of stalk rot.

Diplodia stalk rot is usually found in the central corn belt under conditions of abnormally cool weather during the maturation of corn. Leaves turn into a light grayish color. Lower internodes become brown and spongy. Plants that are killed prematurely produce chaffy and poorly filled grain. Diplodia stalk rot is incited by the fungus Diplodia maydis. Below normal precipitation in June and July followed by excessive precipitation in August and September favor this disease. A balanced nutrient regime and growing of resistant hybrids may minimize losses.

Gibberella stalk rot occurs frequently in the northern and eastern regions of the U.S.A. Symptoms of this disease resemble those of

Diplodia stalk rot. A pink-to-reddish discoloration of the infected parts often distinguishes it from Diplodia stalk rot. The use of resistant full season hybrids can reduce losses due to this disease.

Fusarium stalk rot symptoms are very similar to those of Diplodia and Gibberella stalk rots. A pale pink-to-whitish mycelium sometimes develops at the nodes of infected plant and within the internodes.

Charcoal rot is found in the drier areas where corn is grown. The disease is one of senescence. The outside of the lower internodes becomes a straw colored-to-dark brown. Numerous minute black sclerotia of the pathogen are found scattered over the vascular bundles and inside walls of the stalk. Relatively high soil temperatures and low soil moisture favor the development of charcoal rot.

Black bundle disease symptoms begin to appear after the kernels have reached the dough stage. Purpling of stalk and leaves is one of the first symptoms. Such stalks are usually barren. Multiple ear shoots and tillering are other symptoms. Blackening of the vascular bundles is a positive indication of the disease. The use of high yielding hybrids reduces the black bundle disease symptoms (Ullstrup, 1977).

Pythium root rot is found in poorly drained or compacted soils where oxygen supply is inadequate. The roots turn yellowish-to-brown and are flaccid. Plants are susceptible to this disease at any stage of development. Root rot follows in severe cases of the disease.

Corn is susceptible to a number of ear-rot pathogens. The yield and quality of grain is often reduced. Usually ear-rots do not spread over extensive areas.

An early symptom of Diplodia ear-rot is the bleaching of husks at the butt of the ear. Infection may take place from silking to maturity. The period three to four weeks after silking is most favorable for its onset (Ullstrup, 1977). Frequent rainfall from full silk to four to five weeks thereafter is conducive for the development of the disease. Infected ears are of light weight and husks adhere tightly to one another due to the growth of the fungus between them (Ullstrup, 1977).

Gibberella ear-rot is prevalent during cool, humid weather. During the years 1965 and 1972, Gibberella ear-rot epidemic was extensive (Tuite et al., 1974). A pinkish-to-red mold appears at the tip of the ear and progresses toward the butt. The rot involves all kernels as it develops. Gibberella ear-rot is caused by *Gibberella zeae*. This substance is toxic to swine.

The distinguishing symptom of the disease Nigrospora cob rot is the shredding of the cob. The kernels are usually poorly filled, and pinched at their tips. *Nigrospora oxyzae* is the cause of this disease. This is a weak parasite and attacks ears of plants that are under stress of drought, cold, poor nutrition, or other diseases.

Fusarium kernel rot is especially prevalent in the drier parts of the Corn Belt and in California (Smith and Madsen, 1949). The infected kernels are scattered randomly over the ears. A whitish pink mold also appears. Fusarium ear-rot is caused by *Fusarium moniliforme*.

B.3. Leaf Diseases

The prevalence and severity of leaf diseases depends largely on environmental conditions. In recent years eyespot yellow leaf blight and southern corn leaf blight have increased in prevalence and severity in some areas. Leaf diseases reduce the photosynthetic area of leaves, thereby lowering the yield. The quality of silage is also reduced (Allinson and Washko, 1972).

Moderate temperatures and heavy dew favor the spreading of the northern corn leaf blight; hot, dry weather suppresses it completely. Symptoms of this disease appear as long, elliptical, grayish-green or tan lesions. These lesions then turn into small wilted areas. Temperatures of 77 to 86°F favor their rapid development, under cooler temperatures a longer time is required (Ullstrup, 1977). Spores develop in the necrotic tissue of the lesions during damp weather. The inciting agent of northern corn leaf blight is Helminthosporium turacicum pass. Northern corn leaf blight can be controlled through the incorporation of polygenic and monogenic types of resistance into the inbred lines (Hughes and Hooker, 1971).

The growing season during the 1970 epidemic of the southern corn leaf blight was characterized by the presence of a highly virulent pathogen, warm and humid weather and the extensive cultivation of a uniformly susceptible host. Corn with Texas male-sterile cytoplasm is especially susceptible to this disease. Southern corn leaf blight is caused by Helminthosporium maydis nisik.

Two races of the pathogen, Race T and Race O, exist. Leaf lesions caused by both races are tan and spindle shaped, Race T of the pathogens attacks all parts of the Texas variety corn (Ullstrup, 1977). The use of selective hybrids and foliar spraying reduces the losses due to this disease.

The Yellow leaf blight of corn is usually found in the northern portions of the Corn Belt. Cool, wet weather favors the development of this disease. Yellow leaf blight is caused by Phyllosticta maydis Arny and Nelson. Lesions on the lower leaves have a brown border and buff colored centers. On upper leaves the lesions are narrower. Selective hybrids and clean ploughing control the disease.

Symptoms of corn eye spot appear as oval or circular translucent lesions. With age the centers of these lesions become tan and are surrounded by a reddish brown margin with a narrow yellow halo. Corn debris from the previous year is the primary source of infection.

B.4. Downy Mildew

There are three downy mildew diseases of corn that occur in the U.S.A. Green ear disease is extremely rare. Infected plants become dark green and stocky, leaves develop gray blotches and are chlorotic. Crazy top appears sporadically in all parts of the U.S.A. Concessive tillering and stunting are early symptoms. The normal floral parts in the tassel are replaced by leaves resulting in a bizarre bushy tassel (Ullstrup, 1977). Sorghum downy mildew also develops a bushy tassel, in addition stalks are often brittle and the infected plants are usually barren.

B.5. Corn Smuts

Corn in the U.S.A. is susceptible to common smut. According to Ullstrup (1977) the number, size and location of smut galls determines the amount of yield loss. Smut infection results in smaller ears and kernels. Head smut is not very common in the U.S.A. The tassel and ear are partially or completely converted into a black mass. Proliferation of floral parts in the tassel and ear also occurs.

B.6. Virus Diseases

Virus diseases are generally characterized by either mosaics (mottled leaf surfaces) or stunting of the corn plant. Sometimes the presence of a vector (agent) is needed to transmit the virus.

Sugarcane mosaic (Saccharum virus 1, Smith) is found on corn grown near sugarcane fields. Symptoms generally appear as oval shaped spots assuming a mosaic pattern of light green to yellow streaks. Necrosis and stunting is not observed. The virus is sap transmissible and aphids are known vectors of this virus (Broadbent, 1967).

Maize dwarf mosaic is of considerable economic importance in the U.S.A. The young leaves are mottled, the older ones are chlorotic and reddish. Stunting and proliferation of adventitious buds are also evident. The virus is sap transmissible and aphids are known vectors of this disease (Ullstrup, 1977).

Maize chlorotic dwarf causes chlorotic blotches, splitting of margins of young leaves at right angles to the axis and also stunting. The leafhopper acts as a vector of this virus.

Corn stunt is now believed to be caused by a mycoplasma-like organism (Ullstrup, 1977). Proliferation of tillers and ear shanks, chlorotic spots on young leaves and a general stunting of the plant are the usually observed symptoms of this disease.

Numerous ear shoots and poorly filled ears are the result of an early infection by this disease. Mosaic patterns are not a characteristic of corn corn stunt.

The diseases of corn generally require the presence of a pathogen, a favorable environment and a susceptible host, the presence of a vector is sometimes required. Plants under stress seem to be very susceptible to diseases. A close monitoring of field conditions and sound cultural practices seem to reduce losses due to infestations. Some of the important climate-disease interactions are summarized in Table 2.

C. Important Corn Insects

The corn crop may be subject to insect attacks from the time it is planted until it is harvested. Other crops growing near the corn field are sources of insects that attack corn. Environmental conditions as well as the stage of plant development are some important factors to be considered in monitoring insect activity. The use of effective pesticides and improved corn hybrids has reduced insect populations in recent years.

C.1. Soil Insects

Northern rootworm and Southern rootworm are the two important rootworms of corn in this country. The young larvae feed on root hairs and young lateral roots causing them to turn reddish or brown. The adult rootworm feeds on the crown root buds. The beetles may settle on the silks and hamper pollination (Dicke, 1977). Cultural practices such as crop rotation, fertilization, and adjustment of planting dates reduce rootworm injury.

Cutworms and wireworms feed on seeds and the developing roots. Loss of stand is the initial effect. Overwintering is also evident.

The corn root aphid (Aphis maidiradicis) sucks on the sap from the roots of corn. Dwarfing and yellowing of plants are some of the external symptoms.

DISEASE	STAGES OF INFECTION	CLIMATIC REQUIREMENT	SYMPTOMS
STALK AND ROOT			
Diplodia Stalk Rot	6, 7, 8, 9	Below normal Jun-Jul precipitation followed by above normal Aug-Sep precipitation.	Light gray leaves, brown and spongy internodes.
Gibberella Stalk Rot	6, 7, 8, 9	Same as Diplodia Stalk Rot.	Infected parts pink-to-reddish in color.
Charcoal Rot	9,10	High soil temperature and low soil moisture.	Blackening of the vascular bundles and inside walls of stalk.
Black Bundle	8, 9, 10	Same as Charcoal Rot.	Same as Charcoal Rot.
Phythium Root Rot	1.5-10	Poorly drained or compacted soils.	Roots turn yellow. Root lodging in severe cases.
Diplodia Ear Rot	5-10	*Frequent rains from* silking through four weeks after.	Leaching of husks.
Gibberella Ear Rot	5-10	Cool, humid weather.	A pinkish-to-red mold appears on the ears. Rotting of all kernels.
LEAF			
Northern Corn Leaf Blight	1-6	Moderate temperatures (25-30°C) and heavy dew.	Long elliptical grayish-green or tan lesions appear on leaves followed by wilting.
Southern Corn Leaf Blight	1-6	Warm and humid conditions.	Lesions are tan and spindle shaped.
Yellow Leaf Blight	1-6	Cool and wet weather.	Lesions have brown borders and buff centers.
DOWNY MILDEW			
Crazy Top	1-1.5	Water logged conditions.	A bizarre bushy tassel.
VIRUS			
Maize Dwarf Mosaic	1-6	Warm and humid weather. Aphids act as carriers.	Mottling and chlorosis of leaves. Stunting of the plant.

Table 2. Some Important Climate/Disease Relationships For Corn.

The Sugarcane beetle (Eutheola rugiceps) feeds on the germinating seed and gnaw through the leaf sheaths into the stem near the crown.

C.2. Leaf, Stalk and Ear Insects

The corn earworm (Heliothis zea) larvae feed on the emerging tassel and tip of the ears. The moths lay eggs on the corn leaves, emerging tassel and on fresh silks. According to Valli and Callahan (1966) the insect can withstand large variations in environmental temperatures and therefore has a higher survival rate. The theoretical temperature threshold for development is around 54.7°F (Mangat et al., 1967). Fall ploughing and early planting can reduce the earworm damage (Dicke, 1977).

The European corn borer (Ostrinia nubilalis) was first reported in Massachusetts as early as 1917. The geographical distribution of this species suggests that the European corn borer is adaptable to diverse environmental conditions (Dicke, 1977). Matteson and Decker (1965) claim the threshold of development, under controlled conditions, for the egg stage is about 57.3°F, about 54.5°F for the larval stage and around 52.0°F for the pupal stage.

The European corn borer hibernates as a larva in cornstalks or plant residue. Moth emergence begins around May or June. Low temperatures and high winds limit moth activity. According to Dicke (1977) corn can be infested by either the first or second brood of the corn borer. The stage of development of corn is therefore an important factor in the rate of ovioposition. Early planted corn is susceptible to the first brood and the late maturing variety to the second brood, respectively.

In the early vegetative stage the larvae feed on the sheath and midrib of the leaves. In the later stages they invade the stalk shank and the ear. Symptoms of injury due to larvae include shot-hole and elongated lesions on the leaves, broken tassels and burrows in the stalk. Overwintering of the population can be reduced through ensiling, stalk chopping and ploughing under the residue.

There are four other important corn borers: the Southern cornstalk borer (*Diatraea crambidoides*), the Southwestern corn borer (*Diatraea grandiosella*), the Sugarcane borer (*Diatraea saccharalis*) and Neotropical corn borer (*Diatraea lineolata*).

In the early stages of corn development the larvae attack the unrolled leaves. During the later stages the midribs, sheaths and ears are attacked. Severe injury by these larvae may kill the growing point of the plant. The second and third brood feed on the sheath and ear parts and burrow through the stalk (Dicke, 1977).

Subfreezing temperatures are known to kill the hibernating larvae. The plant residue should be ploughed out in the fall to expose the larvae to freezing temperatures. Crop rotation is also a common practice to reduce the losses.

The Corn leaf aphid (*Rhopalosiphum maidis*) is a small dark bluish-green insect. The wingless form of this aphid attacks the emerging leaves and tassel tip. Large colonies of the winged aphids are found on the leaves and tassels at about pollen shedding and silking time. Anthesis is hampered and may result in barrenness. Prior to tassel emergence, the aphids suck nutrients from the phloem. Aphids are known vectors (carriers) of virus diseases.

The aphids multiply fairly rapidly under cool temperatures. Heavy aphid infestations under a soil moisture stress have been known to cause severe yield reductions (Dicke, 1977).

The Armyworm (*Pseudaletia unipuncta*) larvae first attack the whorls, later on the older larvae feed on the edge of leaves. Armyworm outbreaks are usually local and sporadic.

The Corn flea beetle (*Chaetocnema pulicaria*) feeds on leaves causing long, narrow lesions. These lesions become points of origin of bacterial wilt (Dicke, 1977). Flea beetle injury is often associated with wilting of the plant.

In summary, the insects of corn generally appear locally and sporadically. They are adaptable to diverse environmental conditions and cause most damage when the plant is under stress. Cultural practices such as fall ploughing and ensiling reduce injury. Table 3 shows some of the important insect pests of corn, their climate requirement and type of damage inflicted to the crop.

D. Cultural Practices

D.1. Preplant Tillage

The term tillage refers to the practice of ploughing, sowing and raising crops. Preplant tillage includes ploughing and preparing the seedbed. Some recently developed tillage systems include the chisel, till, strip, rotary and no-tillage. Factors such as labor, power and machinery costs have to be considered before employing any particular tillage system.

The *Moldboard Plow* is widely used for plowing in the fall or spring followed by a secondary tillage before planting. The crop residue

INSECT	STAGES OF INFESTATION	CLIMATIC REQUIREMENT	TYPE OF DAMAGE
SOIL INSECTS			
Rootworm	1.5-6	Mild winters permit overwintering of larvae.	Damage to root hairs and lateral roots. Beetles feed on silks hampering pollination.
Corn Root Aphid	1.5-3	Mild winters permit overwintering of larvae.	Dwarfing, yellowing and reddening of plants.
LEAF, STALK AND EAR INSECTS			
Corn Earworm	1-7	Mild winters and warm summers.	Damage to silks and tip of ear.
European Corn Borer	2-7	Mild winters and warm summers.	Lesions on leaves, broken tassels and burrows in stalk and ear.
Corn Leaf Aphid	1-6	Cool to moderate temperatures of soil moisture stress.	Loss of nutrients from phloem. Anthesis impeded.
Corn Flea Beetle		Adults overwinter. Active when a dry spell is broken by rains.	Lesions on leaves often followed by bacterial wilt.

Table 3. Some Important Insect-Pests of Corn and Their Climatic Requirement and the Type of Damage Inflicted

is generally chopped by a disk harrow and then plowed under. Moldboard plowing is common in the northern Corn Belt or fine-textured soils. Moldboard plowing on poorly drained soils has generally resulted in better yields than from other tillage systems (Griffith et al., 1973).

Chisel Tillage uses the chisel plow with chisel points or sweeps attached to shanks on a heavy frame. Chisel points are used in fall plowing and the sweeps in spring plowing. Water and wind erosion is also reduced by this system of tillage.

In Strip Tillage the soil is tilled in the row zone with either a rotary tiller or a sweep. The strip rotary tiller is combined with a planter, fertilizer, herbicide and insecticide applicators. In the sweep or till planting system the tillage tool and planter are mounted together on the tractor. A wide sweep is made and the bars push residue between rows, a packer wheel places the seed firmly in the soil and disks cover it with soil (Larson and Hanway, 1977).

The advantages of till planting are better erosion control and lower costs. According to Griffith et al. (1973) corn yields from strip rotary and till planting were either equal to or better than moldboard plowing methods on medium and coarse textured soils, well drained soils.

The No-Tillage system incorporates only one tillage and planting operation. Fertilizer is applied near the surface. On erosive soils in the southern areas a winter cover crop is also planted.

Larson and Hanway (1977) feel that corn yields from the no-tillage system, on well drained soils, are better than the moldboard plowing system. Griffith et al. (1973) argue that there is no significant difference in yields if the soils are poorly drained.

D.2. Pattern of Planting

Given a plant population and fertility combination, correct spacing of the plants within and between rows can increase yields by the proper utilization of available moisture and light (Rossman and Cook, 1966).

The Check-Row method of planting consists of placing four seeds equidistant within and between rows. The advantage of this method is the tillage equipment can pass easily between the rows in either direction.

The Drill method consists of singly planted corn spaced at regular intervals. In 1976, 92 percent of the corn in Illinois was planted this way (Illinois Coop. Crop Reporting Service, 1976). In the Hill-Drop technique two or three seeds are spaced at shorter distances within the rows. Crosswise hoeing is not possible in this method. According to the Illinois Cooperative Crop Reporting Service (1976) only seven percent of the corn was hill-dropped during 1976.

D.3. Planting Depth, Plant Population and Row Spacing

Corn is usually planted at a depth of one to three inches. Corn is also planted deeper as the season progresses and soil temperatures increase (Larson and Hanway, 1977). The minimum temperature for the growth of corn is 50^{o}F. Below this temperature there is no germination (Craig, 1977). Allessi and Power (1971) found that the time for 80 percent emergence ranged from four to twenty-four days depending on the soil temperature and seed depth. Temperature had a more pronounced influence on emergence. About 68 growing degree days were required for 80 percent emergence when the seed was placed at a depth of three inches.

The optimum planting rate depends on the hybrid, row width, edaphic and climatic factors. The populations vary from about 16,000 to 40,000 plants per acre (ppa). About 19,190 ppa were planted in Indiana, Iowa, Illinois and Minnesota (Larson and Hanway, 1977).

The leaf area index (LAI) is the ratio of the upper leaf area to the ground area. According to Larson and Hanway (1977) a LAI of about 3.5 seems optimum over a wide range of conditions, as far as corn yields are concerned.

Bondavalli et al. (1970) studied the effects of weather, nitrogen and plant populations on corn yield. Their results indicate that for normal growing season precipitation and a nitrogen application rate of 145.5 lb/acre, the best yield can be obtained by planting at the rate of about 16,950 plants per acre.

Yao and Shaw (1961) studied the effect of plant population and planting pattern of corn on radiation interception and water use. Their results indicate that better yields and less evapotranspiration can be achieved with 28,000 plants using a 21-inch row spacing than with 14,000 plants using a 42-inch spacing.

Larson and Hanway (1977) are of the opinion that corn yields increase as row width decreases from about 39.5 to 20 inches at high plant populations. This could be attributed to the greater interception of solar energy by the leaves.

D.4. Date of Planting

The planting date for corn depends largely on the field conditions. A wet field can prevent the heavy farm equipment from getting into the field. According to Larson and Hanway (1977) it is ideal to plant when the soil temperature at a depth of three inches has reached 59°F for several days. The crop should also mature before the first fall freeze.

Planting date studies with corn in central Missouri by Zuber (1968) indicated April 20 and May 10 as optimum planting dates for yield. Corn yields were reduced when planting was delayed to June 1 or June 10. Zuber claims that a delay in planting can be compensated by planting early maturing varieties. This latter viewpoint is also shared by Hicks et al. (1970) in their experiments with different corn hybrids in southern Minnesota.

Pendleton and Egli (1969) found that in Urbana, Illinois, corn planted on 19 or 30 April yielded better than corn planted on 14 or 31 May. A very early planting was made in the greenhouse on 5 April and transplanted to the field on 19 April; however, the yields were not better than the 19 or 30 April plantings.

In Ames, Iowa, six plantings of corn with relative maturities of 105, 112 and 120 days were made by Marley and Ayers (1972). They found a general trend toward reduced yield with delayed planting. A delay in planting reduced the planting to emergence period for all varieties. The time from emergence to 75 percent silking was also reduced, the later maturing varieties sharing the most decreases.

Improvements in seed quality and weed control practices are now making it possible to plant earlier (Rossman and Cook, 1966; Larson and Hanway, 1977). Very early plantings are not too beneficial. Date of planting is more important in the northern limits of the Corn Belt where the growing season is shorter.

D.5. Selection of Hybrid Corn Seed

The selection of hybrid corn seed is largely dependent on the maturity class and yield characteristics of the seed as well as on the weather prior to planting. Management factors such as the size of farm, labor force on hand and equipment available are some of the other factors to be considered in the selection process (Duncan, 1966).

Most seed companies market their seed specifying the maturity rating for each variety. Such ratings inform the farmer on the time taken by any particular seed variety to attain maturity. Seeds are classified as early, average or late maturing varieties based on their maturity ratings. The late varieties generally have the highest yield potential and the early varieties the least. Therefore, early maturing varieties have to be planted in larger densities in order to achieve high yields.

Growing degree days have been successfully used by several researchers (Gilmore and Rogers, 1958; Mederski et al., 1973; Neild and Seely, 1977) to measure maturity in corn hybrids. For example, Neild and Seely (1977) developed regression equations involving growing degree days to measure the development stages of corn in Nebraska. Such techniques can aid the farmer in planning his field operations ahead of time.

Weather conditions prior to planting also play an important role in the selection of hybrid seed. An early planting date encourages farmers to plant the late maturing high yielding varieties. On the other hand, early maturing varieties are planted if wet weather delays planting by two to three weeks. The farmer should plant only those varieties that should be capable of completing silking and pollination before the onset of moisture stress and high temperatures (above 90^o) which usually occurs in July. Another consideration is that the crop should mature well before the average date for the first fall freeze.

D.6. Fertilizers

> The single largest use of fertilizer in the United States is for corn. Close to 69.5 million acres of corn were harvested during 1977. Fertilization on these required approximately 39 percent of nitrogen, 36 percent of the P_2O_5, and 40 percent of the K_2O used in the United States in 1976/1977. (Fertilizer Situation, 1978)

Clearly, commercial fertilizers are being used extensively in crop production, especially on corn. Relatively low farm commodity prices and government set-aside programs could cause a drop in the trend of fertilizer usage.

According to Larson and Hanway (1977) the appropriate time and method of fertilizer application varies with the materials used and the cultural practices adapted by the farmer. Generally, fertilizers containing N, P, and K are applied in bands two inches to the side and one to two inches below the seed at planting. Soil tests and plant analyses are used for estimating the fertilizer needs for corn.

D.7. Nitrogen

Plants obtain nitrogen through symbiotic and nonsymbiotic nitrogen fixation and from commercial nitrogen fertilizers. In symbiotic nitrogen fixation the nodules produce a substance that attracts the *Rhizobium* bacteria which are capable of fixing nitrogen. Crop rotation by legumes will enrich soil nitrogen through nitrogen fixation by the bacteria. Photosynthetic reduction of nitrogen by photosynthetic bacteria and nonphotosynthetic reduction by bacteria such as Azatobacter include some of the nonsymbiotic processes (Bidwell, 1974).

Nitrogen fertilizer is available in the form of anhydrous ammonia, ammonium nitrate, ammonium sulfate, ammonium phosphate, urea or N solutions. Nitrogen fertilizer may be applied to the soil in fall, winter or at the time of planting. It can also be applied between the rows during the early vegetative stage. Compressed anhydrous ammonia can be applied on either wet or dry soils. Nitrogen solutions contain either urea and ammonium nitrate or anhydrous ammonia and ammonium nitrate in fixed proportions. The solution is then sprayed or dribbled on the soil surface (Kurtz and Smith, 1966). Heavy rains following fertilizer applications can cause considerable leaching of nitrogen. Under waterlogged conditions the nitrate may be denitrified to gaseous forms of N. Larson and Hanway (1977) are of the opinion that spring-applied N is more effective than fall-applied or preplant N.

Powell and Webb (1972) found little advantage for using high concentrations of N, P, and K. The heavier concentrations had undesirable side effects on the soil characteristics and also reduced the yields in subsequent years.

Voss et al. (1970) studied the relationship between grain yield and leaf N, P, and K concentrations for corn. Multivariate regression models using applied N, P, and K percentages and their interaction terms did not explain differences in yield from experimental plots. However, the inclusion of production variables such as plant populations, past cropping and soil water improved their yield models considerably.

Nitrogen is extremely important to plants because it is a constituent of proteins, nuclic acids and other substances. Nitrogen deficiency results in a gradual paling or chlorosis of older leaves, later spreading to the younger leaves. Over fertilization with nitrogen often causes excessive proliferation of stems and leaves followed by a reduction in yield (Bidwell, 1974).

D.8. Phosphorus

Superphosphates and ammonium phosphates are the primary sources of phosphorus fertilizer. Superphosphates are extensively used. The ordinary superphosphate contains about 8.8 percent P (20 percent P_2O_5) and the concentrated superphosphate contains 20 to 22 percent phosphorus (52 to 54 percent P_2O_5) (Caldwell and Ohlrogge, 1966). Ammonium phosphates include a variety of compounds produced by ammoniation of phosphoric acid.

Phosphorus fertilizers can be broadcast applied and plowed under in the fall or spring, at planting time, or as a side dress. Phosphorus reacts readily with iron and aluminum in very acid soils and with calcium in alkaline soils reverting to less soluble forms and moves slowly in the soil. Therefore, the time of application and placement of the fertilizer are important.

Phorphorus-deficiency symptoms in corn show up as a retarded rate of growth and slow maturity. The silks emerge slowly and defective ears are produced. Pollination is often poor resulting in unfilled kernels (Caldwell and Ohlrogge, 1966; Peaslee et al., 1971).

D.9. Potassium

Potassium chloride is the main source of potassium in corn. The fertilizer can be broadcast and plowed under or disked into the soil surface before planting, or placed as a band at planting time. Potassium can be applied every year or in larger amounts once in several years.

In potassium deficient young plants the leaves are light green in color or have yellow streaks. The margins of lower leaves appear scorched or fired. As the plant ages, the symptoms spread upward, sometimes the lower leaves may die. The ears are usually small and unfilled at their tips. Lodging results when the plant is permanently broken down from the vertical posture by winds. More often premature lodging occurs as a result of stalk rot, root rot or corn borer infestation (Zuber, 1968). Barber and Mederski (1966) claim that lodging and stalk rots are often associated with the level of potassium in the plant.

Some of the important fertilizer-yield relationships for corn, at various stages of growth and development, are summarized in Table 4.

D.10. Weed Control

Weeds compete with corn plants for nutrients and water. Behrens and Lee (1966) claim that yield reductions by weeds can range from 16 to 93 percent. Mechanical cultivation of weeds could reduce losses to about 4 to 41 percent.

Mechanical cultivation of corn after planting to reduce weeds can be accomplished with shovel cultivators, rotary cultivators, disk culivators, rotary hoes and spike tooth harrow (Larson and Hanway, 1977).

Chemical control of weeds is achieved by applying selective herbicides. Herbicide applications are classified as preplant, preemergence or post-emergence treatments. Atrazine and Butylate are widely used preplant herbicides. Combined applications of Atrazine and Butylate can be very effective on broadleaf and grass-weed seedlings. The widely

STAGE	FERTILIZER--CLIMATE/YIELD INTERACTIONS
Preplant	Base fertilizer application rates on soil tests. Excess precipitation may cause leaching of fertilizer.
Planting to 0.0	Too much fertilizer near seed can lead to salk injury to seedling.
0.5 to 3.0	N deficiency--Plants light green, lower leaves yellow, stalks short and slender. P deficiency--Plants dark green, lower leaves yellow, stalks short and slender. K deficiency--Mottled or chlorotic leaves, necrotic spots, slender stalks.
3.0 to 4.0	Nutrient deficiency reduces number of ovules that form silks. Excess N and inadequate K levels may cause stalk breakage.
4.0 to 5.0	Nutrient deficiency delays silking and leads to poor pollination and seed set. K uptake is complete.
5.0 to 9.0	K deficiency will lead to unfilled kernels at tip of ear and also chaffy ears.
9.0 to 10.0	Dry matter accumulation nearly complete.

Table 4. Fertilizer and Climate/Yield Interactions at Various Stages of Growth and Development of Corn

used pre-emergence herbicides are Alachlor, Atrazine, Propachlor and Cyanazine. Combinations of Alachlor or Propachlor with Atrazine or Cyanazine can effectively control all annual weeds in corn. Post-emergence herbicides are 2, 4-D, Dicamba, Atrazine and Cyanazine. 2, 4-D is the most widely used post-emergence herbicide for broadleaf weeds (Larson and Hanway, 1977). Rainfall after herbicide treatment is necessary to disperse the herbicide in the surface layers of the soil.

D.11. Harvesting

Corn harvest begins after maturity when the corn kernels have attained the required moisture content. Corn for silage is harvested at moisture levels of 28 to 32 percent. For storage the moisture content should be between 20 to 25 percent. An early harvest may avoid losses due to dropped ears, stalk lodging, ear-rots and insects (Larson and Hanway, 1977). Wet weather around harvest time may prevent the combines from getting onto the field.

Corn is harvested by means of the picker, picker-sheller or the combine. Most of the corn in Iowa and Illinois is harvested with the combine (Iowa Crop Livestock Reporting Service, 1977; Illinois Coop. Crop Reporting Service, 1977). The corn combine and picker-sheller picks, husks, shells and delivers the corn in one operation.

In short, sound cultural practices such as planting early, efficient weed control, supplying adequate nutrients and an early harvest ensure a good harvest. In case of unfavorable weather good cultural practices will minimize the resulting losses.

CHAPTER III

DATA ANALYSIS AND METHODOLOGY

A. Organization of the Data Base

The basic data set for Iowa and Illinois consists of station-level daily precipitation and temperature data, state and crop reporting district (CRD) level yield data, and state level fertilizer and phenology data. Due to a sparse available network of stations in Iowa and Illinois, the CRDs have to be aggregated into larger crop regions called macro-CRDs. Weekly averages of precipitation and temperature as well as their derived variables are computed for each year. Weather effects at stages critical to plant growth and development are then computed from the weekly phenological and climatological data. These variables form the inputs to the various models. A non-linear trend is fitted to the yield data in order to accommodate any future leveling off in yields. Applied nitrogen fertilizer formed the other alternate trend term.

A.1. Crop Regions

The nine CRDs in Iowa have been aggregated into two macro-CRDs, Iowa-West and Iowa-East, as shown in Figure 2. Eight meteorological stations were available to represent Iowa-West and fourteen stations to represent Iowa-East.

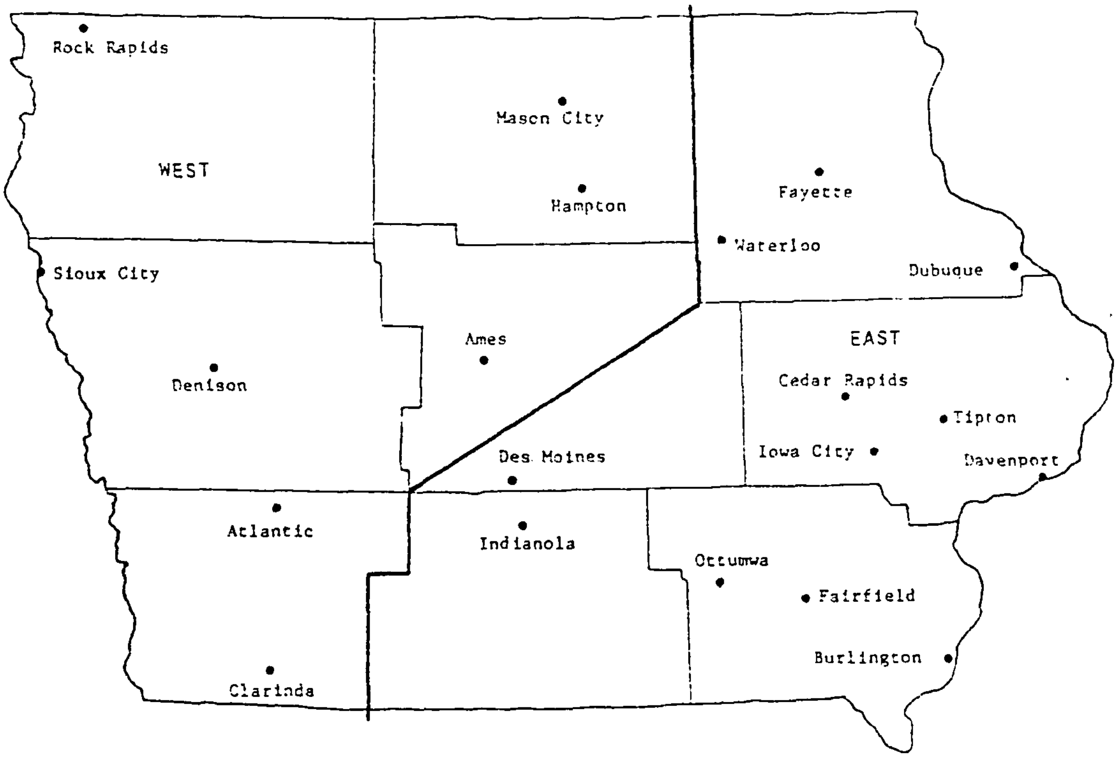

Figure 2. Iowa State CRD and Macro-CRD Boundaries Showing Meteorological Station Locations.

In Illinois, the nine CRDs have been combined into three macro-CRDs as shown in Figure 3. Illinois-North includes twelve meteorological stations, Illinois-Central has nine and Illinois-South only three stations.

A.2. Yield Data

Corn yield is generally expressed in units of bushels per harvested acre (Bu/Acre). According to the *Iowa Agricultural Statistics* (Iowa Crop and Livestock Reporting Service, 1976), a bushel of corn, by convention, contains 56 pounds of shelled corn.

Iowa corn yield data at the CRD and state levels are reported annually in *Iowa Agricultural Statistics* (Iowa Crop and Livestock Reporting Service, 1929-1976). These are available at the Iowa State Statistical Reporting Services (SRS) and at the Center for Climatic and Environmental Assessment (CCEA), Columbia, Missouri. The macro-CRD yield for each year Y*(macro-CRD) is obtained from the appropriate regular CRD yield Y(CRD) as follows:

$$Y^*(\text{Iowa-West}) = (Y(NW) + Y(NC) + Y(WC) + 0.5\,Y(C) + Y(SW))/4.5 \tag{1}$$

$$Y^*(\text{Iowa-East}) = (Y(NE) + 0.5\,Y(C) + Y(EC) + Y(SC) + Y(SE))/4.5 \tag{2}$$

Illinois corn yield data at the CRD and state level are reported annually in *Illinois Agricultural Statistics* (Illinois Cooperative Crop Reporting Service, 1925-1976). The macro-CRD yields can be computed from the nine CRD yields as follows:

$$Y^*(\text{Illinois-North} = (Y(NW) + Y(NE))/2 \tag{3}$$

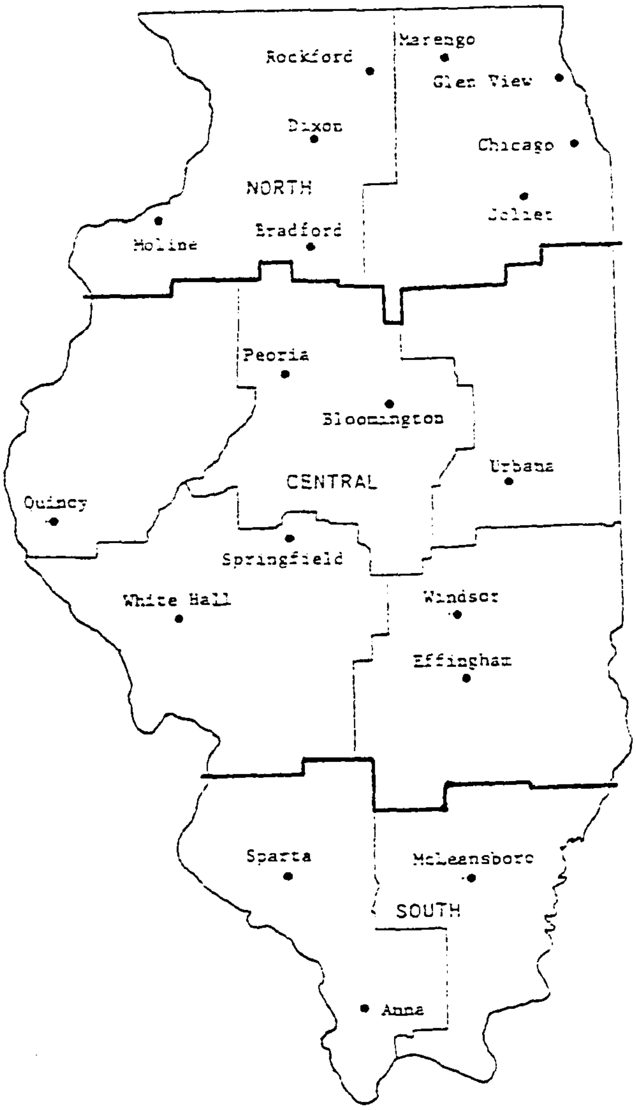

Figure 3. Illinois State CRD and Macro-CRD Boundaries Showing Meteorological Station Locations.

$$Y^{*}(\text{Illinois-Central}) = (Y(W) + Y(C) + Y(WSW) + Y(E) + Y(ESE))/5 \tag{4}$$

$$Y^{*}(\text{Illinois-South}) = (Y(SW) + Y(SE))/2 \tag{5}$$

The Iowa and Illinois yield data sets cover the periods 1929-1976 and 1925-1976, respectively. Due to limitations on fertilizer data, the yield data over the period 1949-1976 alone has been utilized.

B. Fertilizer Data

The three kinds of fertilizers generally applied on corn are nitrogen, phosphate (P_2O_5) and potash (K_2O). State level fertilizer application rates for corn are published annually in the Fertilizer Situation (USDA, Economic Research Service, 1971-1976). Data for the period 1964-1970 are published in Cropping Practices (USDA, Statistical Reporting Service, 1971). Prior to 1964 only census data for the years 1947, 1954 and 1959 are available (USDA, 1947, 1954 and 1959). It is reasonable to make linear interpolations for the fertilizer data between 1949 and 1963 by making use of the 1947, 1954, 1959 and 1964 data. The shift in technology took place around 1955 (McQuigg, 1975). Prior to 1955 fertilizer application rates were relatively low.

Fertilizer data at the CRD level are not presently available. State values have to be used for this purpose. The subsequent CRD yield models will not be sensitive to intra-state variations in fertilizer usage.

C. Meteorological Data

The meteorological station location for Iowa and Illinois are shown in Figures 2 and 3, respectively. These stations report the daily precipitation, and maximum and minimum temperatures. Some of these stations have been in operation since 1900 or even earlier. The raw meteorological data tapes of daily data for the period 1901-1976 have been purchased from the National Climatic Center at Asheville, North Carolina, by CCEA. The weekly statistics for the raw meteorological data as well as their derived variables are computed and stored on magnetic tape. The flow diagram for the meteorological data is shown in Figure 4.

C.1. Missing Data

The raw meteorological data tapes have been processed to determine any discontinuties in the time series. Missing data are usually identified by gaps in the time series. Sometimes missing observations are indicated by the presence of special codes. A detailed listing of the missing data for each station as well as the required software is reported in an earlier study by Eddy and Achutuni (1977). No attempt has been made to restore the missing data. Instead, the number of actual reports used in computing the weekly statistics is provided.

C.2. Weekly Statistics

The next step involves the computation of weekly statistics of the daily meteorological data for each macro-CRD. The 46 stations in Iowa and Illinois are assigned to their corresponding macro-CRDs. The weekly statistics are computed and stored on magnetic tape in the following manner.

Column 1 The macro-CRD number (Refer to Table 5).

Column 2 The year.

Column 3 The week (week 1 = January 1 - January 7).

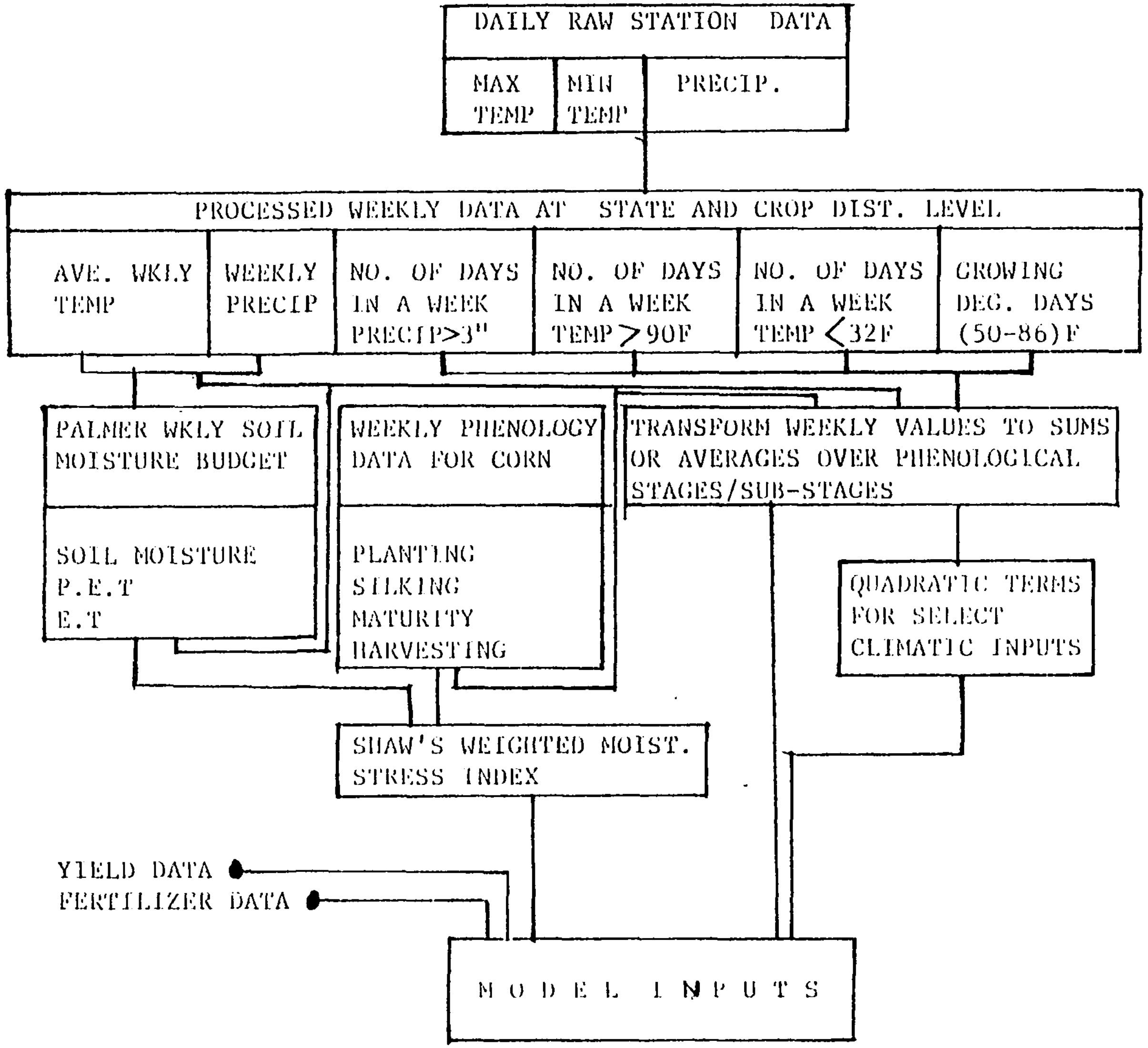

Figure 4. Flow Chart Showing the Steps Involved in Transforming Raw Meteorological Data into Model Inputs

CD	YEAR	WK	PVAR	PSTDV	HUMRL	P>3IN.	P>.01	TRAIN	TVAR	TSTDV	HUMTL	T>90F	T<32F	GDD
1	1973	1	66.0	0.0	35.0	0.0	2.0	2.0	9.5	11.6	33.0	0.0	7.0	0.0
1	1973	2	4.0	3.8	35.0	0.0	1.0	1.0	8.1	12.2	32.0	0.0	7.0	0.0
1	1973	3	27.8	18.6	35.0	0.0	2.0	2.0	14.5	6.2	35.0	0.0	6.0	0.0
1	1973	4	71.0	0.0	35.0	0.0	3.0	3.0	20.4	7.0	35.0	0.0	7.0	0.0
1	1973	5	93.8	46.5	35.0	0.0	2.0	2.0	27.3	6.5	35.0	0.0	7.0	0.0
1	1973	6	10.6	5.2	35.0	0.0	2.0	2.0	21.2	7.5	32.0	0.0	7.0	0.0
1	1973	7	53.4	0.0	35.0	0.0	3.0	3.0	17.6	12.1	34.0	0.0	7.0	0.0
1	1973	8	0.0	0.0	35.0	0.0	0.0	0.0	31.7	5.6	35.0	0.0	7.0	0.0
1	1973	9	5.2	4.0	35.0	0.0	1.0	1.0	35.9	5.5	35.0	0.0	4.0	0.0
1	1973	10	138.4	0.0	35.0	0.0	6.0	6.0	39.4	3.1	35.0	0.0	4.0	0.0
1	1973	11	78.0	0.0	35.0	0.0	3.0	3.0	42.2	8.1	35.0	0.0	4.0	5.2
1	1973	12	98.8	0.0	35.0	0.0	3.0	3.0	41.3	3.9	35.0	0.0	5.0	0.0
1	1973	13	99.0	0.0	35.0	0.0	5.0	5.0	44.0	4.2	35.0	0.0	4.0	0.2
1	1973	14	25.2	0.0	35.0	0.0	3.0	3.0	41.3	5.9	35.0	0.0	4.0	3.4
1	1973	15	103.4	0.0	35.0	0.0	3.0	3.0	38.7	9.1	35.0	0.0	4.0	3.0
1	1973	16	144.4	89.6	35.0	1.0	1.0	3.0	55.1	7.4	35.0	0.0	1.0	45.4
1	1973	17	24.0	17.5	35.0	0.0	3.0	3.0	52.1	6.1	35.0	0.0	2.0	25.4
1	1973	18	138.0	0.0	35.0	0.0	5.0	5.0	53.3	7.0	35.0	0.0	1.0	35.0
1	1973	19	141.0	0.0	35.0	0.0	4.0	4.0	56.9	5.0	35.0	0.0	0.0	49.2
1	1973	20	0.2	1.1	35.0	0.0	1.0	0.0	57.3	7.0	35.0	0.0	1.0	53.8
1	1973	21	105.6	0.0	35.0	0.0	5.0	5.0	62.2	6.5	35.0	1.9	0.0	84.4
1	1973	22	106.2	0.0	35.0	0.0	4.0	4.0	61.9	5.4	34.0	0.0	0.0	97.0
1	1973	23	32.8	19.4	35.0	0.0	2.0	2.0	72.4	6.0	35.0	4.0	0.0	146.6
1	1973	24	78.4	0.0	35.0	0.0	4.0	4.0	74.9	4.6	35.0	4.0	0.0	165.8
1	1973	25	101.2	44.0	35.0	0.0	2.0	2.0	68.5	5.0	35.0	2.0	0.0	125.2
1	1973	26	39.2	[illegible]	35.0	0.0	2.0	2.0	71.5	5.2	35.0	2.0	0.0	146.8
1	1973	27	176.6	0.0	35.0	0.0	3.0	1.0	77.1	2.8	35.0	1.0	0.0	180.4
1	1973	28	63.0	19.8	35.0	0.0	2.0	2.0	75.2	5.0	35.0	4.0	0.0	167.2
1	1973	29	197.2	0.0	35.0	0.0	5.0	5.0	70.1	4.4	35.0	1.0	0.0	139.2
1	1973	30	86.2	12.4	35.0	0.0	4.0	4.0	71.8	2.8	35.0	0.0	0.0	152.2
1	1973	31	52.8	71.6	35.0	0.0	2.0	2.0	69.5	3.7	35.0	0.0	0.0	135.0
1	1973	32	129.4	69.3	35.0	0.0	5.0	5.0	73.7	2.8	35.0	2.0	0.0	163.4
1	1973	33	40.8	0.0	35.0	0.0	1.0	2.0	73.5	3.7	35.0	2.0	0.0	159.0
1	1973	34	92.2	62.2	35.0	0.0	1.0	3.0	72.9	4.1	35.4	2.0	0.9	155.4
1	1973	35	39.6	10.0	35.0	0.0	3.0	1.0	77.0	2.6	35.0	1.0	0.0	180.2
1	1973	36	169.2	9.0	35.0	0.0	3.0	1.0	66.0	3.8	35.0	0.0	0.0	112.0
1	1973	37	81.4	0.0	35.0	0.0	1.0	1.0	59.3	5.7	35.0	0.0	0.0	66.6
1	1973	38	62.8	0.0	35.0	0.0	1.0	1.0	57.0	6.8	35.0	0.0	0.0	50.8
1	1973	39	404.2	0.3	35.0	1.0	7.0	7.0	62.1	3.9	35.0	0.0	0.0	84.6
1	1973	40	33.6	0.0	35.0	0.9	4.0	1.0	58.0	4.1	35.0	0.0	0.0	56.4
1	1973	41	268.0	0.0	35.0	1.0	4.0	4.0	62.6	7.4	35.0	0.0	0.0	88.2
1	1973	42	0.0	0.0	35.0	0.0	0.0	0.0	54.5	5.7	35.0	0.0	2.0	37.0
1	1973	43	14.6	12.1	35.0	0.0	2.0	2.0	55.7	8.3	35.0	0.0	0.0	51.4
1	1973	44	11.7	0.0	31.0	0.0	2.0	2.0	39.9	4.5	31.0	0.0	3.0	0.0
1	1973	45	0.5	0.9	20.0	0.0	1.0	1.0	31.4	6.4	20.0	0.0	6.0	0.0
1	1973	46	23.5	0.0	28.0	0.0	2.0	2.0	45.9	6.8	20.0	0.0	2.0	8.3
1	1973	47	156.8	0.0	28.0	0.0	1.0	3.0	39.6	5.0	28.0	0.0	5.0	0.3
1	1973	48	20.5	5.7	10.0	0.0	2.0	2.0	38.1	5.2	30.0	0.0	5.0	0.8
1	1973	49	77.0	0.0	35.0	0.0	3.0	3.0	24.4	8.6	35.0	0.0	7.0	0.0
1	1973	50	20.4	0.0	35.0	0.0	3.0	3.0	18.5	7.7	35.0	0.0	7.0	0.0
1	1973	51	12.0	21.6	35.0	0.0	1.0	1.0	14.5	8.0	34.0	0.0	7.0	0.0
1	1973	52	80.2	0.0	35.0	0.0	4.0	4.0	21.5	9.1	35.0	0.0	7.0	0.0

Table 5. Sample Output of Weekly Weather Statistics for Iowa-West During 1973.

Column 4 The precipitation averaged over the macro-CRD and totalled over the week.

$$PBAR = 7*(\sum_{i=1}^{N} p_i)/N \qquad (6)$$

where N denotes the total number of precipitation reports in the week and p_i is the ith report.

Column 5 Root mean square (RMS) value for weekly precipitation (This column is not currently in use).

Column 6 The number of reports in computing PBAR for that week.

Column 7 The number of days during the week when at least one station reported over three inches of precipitation.

Column 8 The number of days during the week when at least one station reported over .01 inches of precipitation.

Column 9 The number of rainy days during the week.

Column 10 The average temperature for the week over the area.

$$TBAR = \sum_{i=1}^{N} (T_{max} + T_{min})_i/2)/N \qquad (7)$$

where T_{max} and T_{min} are the daily maximum and minimum temperatures, and N, the number of reports over the area during the week.

Column 11 The standard deviation of the individual $(T_{max} + T_{min})_i$ about the mean TBAR.

Column 12 The number of reports, N, used in calculating TBAR.

Column 13 The number of days during the week when at least one station has a temperature above 90^oF.

Column 14 The number of days during the week when at least one station has a temperature below 32^oF.

Column 15 The number of growing degree days (GRDD) during the week averaged over the macro-CRD.

$$GRDD = 7* \sum_{i=1}^{N} (((T_{max} + T_{min})_i/2)-50)/N \qquad (8)$$

subject to the following constraints:

$(T_{max} + T_{min})_i/2 > 50^oF$ and if $T_{max} > 86^oF$, then $T_{max} = 86^oF$.

D. Soil Moisture

Soil moisture for this study is computed on a weekly basis from the precipitation and temperature data using a hydrologic accounting system similar to the one reported by Palmer (1965). More complicated methods of estimating soil moisture are available (Baier et al., 1972; Shaw, 1963), but the data required to run such models over large areas are not generally available at present.

The present use of soil moisture is as a predictor variable in a linear regression equation and hence it is the deviations of this variable about its linear trend which are considered important. Small differences between the estimated PET long-term mean and its actual value will not make significant differences to the end results (Eddy and Achutuni, 1978). Moreover, soil moisture variables have been included in the present study only for evaluating the budgeting technique.

In this study potential evapotranspiration (PET) is determined using the Thornthwaite (1948) methodology and compared with values published by Palmer (1965). PET (in inches for week i) is given by:

$$PET_i = ((1.6(5.556(T_i-32)/B)^{A}HOURS/12)/2.54/(30/7)) \qquad (9)$$

where

T_i = weekly CRD average temperature in ^oF (PET = 0 when $T < 32^oF$),

HOURS = number of daylight hours,

7/30 = transformation from monthly values used by Thornthwaite to weekly values used in this study.

$A = .49239 + .01792B - .0000771B^2 + .000000675B^3$, and

B = the heat index

$$= (1/4) \sum_{i=1}^{52} ((\overline{T}_i - 32)/5)^{1.514}$$

where $\overline{T}_i$ = long-term weekly CRD average temperature in ^{o}F

and $\overline{T}_i$ is set = 32 if $T_i < 32^{o}F$.

The soil profile is divided into two arbitrary layers. The undefined upper layer, called surface soil and roughly equivalent to the plough layer, is assumed to hold one inch of available moisture at field capacity. It is assumed that evapotranspiration takes place at the potential rate from this surface layer until all the moisture is depleted, then moisture is drawn from the underlying layer. In reality, however, roots withdraw moisture simultaneously from both the layers. Loss from the underlying layer depends on the initial moisture content as well as on the available water capacity (AWC) of the soil. The AWC values for Iowa and Illinois were provided by Lyle Denny of the National Weather Service and are tabulated below in Table 6.

MACRO-CRD	AWC
Iowa-West	10
Iowa-East	10
Illinois-North	10
Illinois-Central	10
Illinois-South	9

Table 6. AWC Values in Inches

Further, it is assumed that no runoff occurs until both layers reach field capacity. Again this is not an entirely satisfactory assumption. Water loss from the two layers, during any particular week, can be computed as follows:

$$L_s = S_s' \text{ or } (PET - P) \qquad (10)$$

whichever is smaller and

$$L_u = (PET - P - L_s)\ \frac{S_u'}{AWC},\ L_u \leq S_u \qquad (11)$$

where

L_s = moisture loss from the surface layer,

S_s' = available moisture stored in the surface layer at the beginning of the week,

PET = potential evapotranspiration for the week,

P = precipitation for the week,

L_u = loss from the underlying layer,

S_u' = available moisture stored in the underlying layer at the beginning of the week, and

AWC = combined available water capacity for both the layers.

The maximum water requirements of a region are estimated by Thornthwaite's formula. Palmer (1965) claims that the average percent absolute error involved is approximately 10 to 15 percent for periods of about two weeks or longer. As pointed out earlier, it is the deviations about the long-term trend that are of importance in the present context and not the absolute values. The AWC values vary markedly from soil to soil; therefore, the use of regional AWC values in this analysis has to be treated with some caution. In view of the assumptions made and the inherent model limitations, results from this technique are applicable only to large areas. The use of soil moisture from this technique is limited to linear regression models.

E. The Need for a Phenological Time Scale

Weather effects at critical stages of corn growth and development have been studied by several researchers (Denmead and Shaw, 1960; Hanway, 1971; Shaw, 1977). In order to realistically model weather effects on corn yields, the weather variables should be explicitly related to the observed phenological stages of the crop; in other words, the weather inputs have to be transformed from a "fixed calendar" to a "phenological" time scale.

For example, a delay in planting can reduce corn yields (Zuber, 1968). This is because pollination is, by then, delayed to a time when moisture stress and high temperatures are likely to cause kernel abortion. Weather inputs based on a fixed calendar scale will then be out of phase with the observed stage of crop development, whereas the variables based on a phenological time scale are automatically adjusted to such time lags.

E.1. Transformation of Weather Variables from a Fixed Calendar to a Phenological Time Scale

In order to model weather effects on corn yields at critical stages of crop development, the weekly weather inputs have to be referred relative to the observed phenological stages. Planting, silking and maturity are the three important phenological stages considered in this study. Phenological data for the other crop stages are not available at present.

In this study, the temperature variables have been obtained from the average weekly temperature values as follows:

$$T_j = \sum_{i=a}^{b} \overline{T}_i/(b-a) \tag{12}$$

where

T_j = the average temperature (°F) during the summation interval (a, b) for the jth variable ($j = 1, 2, \ldots, 6$),

$\overline{T}_i$ = the average weekly temperature (°F) during the ith week,

a = ($s \pm m$) the lower bound for the summation index i,

b = ($s \pm n$) the upper bound for i,

s = the observed stage of the crop (P = planting, S = silking and M = maturity),

m = the number of weeks prior to (-) or after (+) stage s, and

n = the number of weeks prior to (-) or after (+) stage s, subject to the constraint $b > a$. (Refer to Table 7 for the corresponding a and b values for each of the j variables.)

Temperatures in excess of 90°F around silking are known to cause kernel abortions and poor grain filling (Hanway, 1971; Shaw, 1977). The number of days in a week, during silking, that exceed 90°F can be considered as a measure of temperature stress. In this study, temperature stress has been parameterized as follows:

$$T90_j = \sum_{i=a}^{b} NT90_i \tag{13}$$

where

$T90_j$ = the total number of days when the maximum daily temperature (Tx) exceeded 90°F during the interval (a, b) for the jth variable ($j = 1, 2$),

$NT90_i$ = the number of days during the ith week when $Tx > 90^oF$,

and

a, b values are given in Table 7 for each of the j variables.

Freezing temperatures after emergence can kill the young plants and reduce yields, unless followed by replanting. An early freeze before physiological maturity may lead to yield losses (Shaw, 1977). In this study, yield reductions due to freezing temperatures are parameterized as follows:

$$T32_j = \sum_{i=a}^{b} NT32_i \tag{14}$$

where

$T32_j$ = the total number of days when the minimum temperature (Tn) fell below 32^oF during the period (a, b) for the jth variable (j = 1, 2),

$NT32_i$ = the number of days during the ith week when $Tn < 32^oF$,

and

a, b values for the j variables are listed in Table 7.

Precipitation variables are divided into two categories. The first category refers to stages up to and including silking, and the second category considers stages after silking.

Precipitation around planting delays planting operations. Late planted corn generally yields less because silking may be delayed until much of the pollen has been shed (Hanway, 1971; Shaw, 1977). Root rot and stalk lodging is very common if flooding occurs during the vegetative stages of growth. After the vegetative stage there is no yield reduction (Zuber, 1968). In this study, the precipitation variables till silking

VARIABLE	PERIOD COVERED	
	a	b
Temperature:		
T_1	3 Wks before PLTG	PLTG
T_2	1 Wk after PLTG	2 Wks after PLTG
T_3	3 Wks after PLTG	6 Wks after PLTG
T_4	4 Wks before SILK	3 Wks before SILK
T_5	2 Wks before SILK	1 Wk after SILK
T_6	2 Wks after SILK	5 Wks after SILK
$T90_1$	2 Wks before SILK	1 Wk after SILK
$T90_2$	2 Wks after SILK	5 Wks after SILK
$T90_{12}$	2 Wks before SILK	5 Wks after SILK
$T32_1$	3 Wks after PLTG	6 Wks after PLTG
$T32_2$	6 Wks after SILK	MAT
Soil Moisture:		
SM1	6 Wks before SILK	7 Wks after SILK
SM2	6 Wks before SILK	3 Wks after SILK
SM3	2 Wks before SILK	1 Wk after SILK
Moisture Stress:		
S	6 Wks before SILK	3 Wks after SILK

Table 7. List of Independent Variables Tested in the Development of the Individual Models. a and b are the Lower and Upper Limits in Time over Which Variable is Applicable (PLTG = Planting, SILK = Silking and MAT = Maturity)

VARIABLE	PERIOD COVERED	
	a	b
Precipitation:		
P_1	3 Wks before PLTG	PLTG
P_2	1 Wk after PLTG	2 Wks after PLTG
P_3	3 Wks after PLTG	6 Wks after PLTG
P_4	4 Wks before SILK	3 Wks before SILK
P_5	2 Wks before SILK	1 Wk after SILK
R_1	2 Wks after SILK	5 Wks after SILK
R_2	6 Wks after SILK	MAT
R_3	1 Wk after MAT	2 Wks after MAT
R_4	3 Wks after MAT	----
R_5	4 Wks after MAT	----
R_6	5 Wks after MAT	----
R_{45}	3 Wks after MAT	4 Wks after MAT
Quadratic:		
P_3Q	3 Wks after PLTG	6 Wks after PLTG
P_5Q	2 Wks before SILK	1 Wk after SILK
Interaction Term:		
P_5T90	2 Wks before SILK	1 Wk after SILK

are given by:

$$P_j = \sum_{i=a}^{b} PCP_i \tag{15}$$

where

P_j = the total precipitation (inches) during the period (a, b) for the jth variable (j = 1, 2, ..., 5),

PCP_i = the total precipitation during the ith week (inches), and

the values for a and b are given in Table 7.

After silking there is a rapid increase in the dry matter accumulation rate. Moisture stress during the dough and dent stages results in poor grain filling and "chaffy" ears. At maturity, the dry matter accumulation ceases. After maturity moisture is not at all important. Heavy precipitation around harvest time can delay harvesting and yield losses due to dropped corn ears are common (Hanway, 1977; Shaw, 1977). The precipitation variables, after silking, have been selected to represent the above mentioned situations as closely as possible (refer to Table 7).

$$R_j = \sum_{i=a}^{b} PCP_i \tag{16}$$

where

R_j = the total precipitation (inches) during the period (a, b) for the jth variable (j = 1, 2, ..., 6),

PCP_i = the total precipitation during the ith week (inches), and

the a and b values are given in Table 7.

Flooding of fields during the early vegetative stage may cause root rot and stalk lodging (Zuber, 1968). The amount of yield reduction depends upon the duration of flooding. During the late vegetative stage, yield reductions due to flooding are negligible if sufficient nitrogen is present in the soil (Shaw, 1977). Flooding during the vegetative stage has been parameterized in this study as follows:

$$P3_j = \sum_{i=a}^{b} NPCP3_i \tag{17}$$

where

$P3_j$ = the total number of times the observed daily precipitation exceeded three inches during the period (a, b) for the jth variable (j = 1, 2),

$NPCP3_i$ = the number of days precipitation exceeded three inches during the ith week, and

the values of a and b for the j variables are given in Table 7.

E.2. Soil Moisture During Silking and Pollination Stages

Severe moisture stress during flowering may delay silking until after much of the pollen has been shed, resulting in an increase in the number of barren stalks and poorly filled ears (Shaw, 1977). In general, the cumulative soil moisture between any two stages is given by:

$$SMj = \sum_{i=a}^{b} SOILM_i \tag{18}$$

where

SMj = the cumulative soil moisture (inches) between the phenological stages a and b for the jth soil moisture variable (j = 1, 3),

$SOILM_i$ = the soil moisture during the ith week, and

the a, b values for the j variables are listed in Table 7.

E.3. Modified Shaw's Weighted Moisture Stress Index

Shaw (1974) is of the opinion that moisture stress at different stages of corn development will differentially affect yields. He developed weighting factors for various five-day periods before and after silking and computed the cumulative stress over an 85-day period as follows:

$$S' = \sum_{j=s_1}^{s_2} \sum_{i=1}^{5} \{1-ET_i/PET_i\}*W_j \qquad (19)$$

where

S' = the accumulated moisture stress index over an 85-day period,

PET_i = the potential evapotranspiration for the ith day during the five-day period,

ET_i = the actual evapotranspiration for the ith day,

W_j = the appropriate weight for the jth five-day period,

s_1 = eight (number of five-day periods before silking), and

s_2 = nine (number of five-day periods after silking).

The present soil moisture budget uses weekly time steps; therefore, Equation (19) has to be modified to use weekly soil moisture values as follows:

$$S = \sum_{j=s_1}^{s_2} 7*\{1-ET_j/PET_j\}*W_j \qquad (20)$$

where

S = the modified stress index,

PET_j = the average potential evapotranspiration for the jth week,

ET_j = the average actual evapotranspiration for the jth week,

W_j = the appropriate weight for the jth week,

s_1 = six (weeks before silking), and

s_2 = seven (weeks after silking).

The weighting factors are given in Table 8.

No. of Weeks Before Silking	Weighting Factor	No. of Weeks After Silking	Weighting Factor
6	0.50	1	2.00
5	0.50	2	1.30
4	1.00	3	1.30
3	1.00	4	1.30
2	1.75	5	1.20
1	2.00	6	1.00
0	2.00	7	0.50

Table 8. The Weighting Factors (W_j) Used to Evaluate Stress Effects on Corn Yields (After Shaw, 1974)

It should be noted that the modified stress index (S) is a measure of the average weekly stress, a factor of seven has been introduced in Equation (20) only for scaling purposes.

E.4. Quadratic and Interaction Terms

The curvilinear relationship between certain weather variables and crop yields at various stages of crop development have been reported by several authors (Baier, 1973; Eddy, 1977; McQuigg, 1975; Thompson, 1962 and 1969). A few quadratic terms for precipitation have been included in this study.

A slight moisture stress during the early vegetative stage results in a well developed root system. Whereas excess precipitation causes exuberant vegetative growth and very poor floral development, thereby reducing yields (Shaw, 1977). Excess precipitation or too little of it during the tasseling, silking and pollination period can lead to poor pollination and reduced yields (Hanway, 1971; Shaw, 1976). In this study, such curvilinear relationships have been parameterized as follows:

$$P_jQ = \sum_{i=a}^{b} \{1-((P_{ji}-\overline{P}_j)/\sigma_{P_j})^2\} \tag{21}$$

where

P_jQ = the quadratic form for the jth precipitation variable (j = 3 or 5),

P_{ji} = the observed precipitation for the ith week and jth variable,

$\overline{P}_j$ = the average precipitation during the period (a, b) for the jth variable,

σ_{P_j} = the standard deviation of P_{ji}, and the corresponding a, b values are given in Table 7.

The interaction between precipitation and high temperatures around silking is of importance to corn yield. Below normal precipitation accompanied by high temperatures ($Tx > 90^oF$) can lead to delayed silking and poor pollination. Whereas above normal precipitation accompanied by above normal temperatures may have a less deleterious effect on corn yields. The following equation has been developed in this study to account for the interaction between precipitation and high temperatures.

$$P_5T90 = \sum_{i=a}^{b} NT90_i(P_{5_i} - \overline{P}_5) \qquad (22)$$

where

P_5T90 = the interaction between precipitation and high temperatures at silking,

P_{5_i} = the precipitation around silking during the ith week,

$\overline{P}_5$ = the average precipitation during the period (a, b),

$NT90_i$ = the number of days $Tx > 90^{o}F$ during the period (a, b), and

the limits for a and b are given in Table 7.

E.5. Phenological Inputs to the Models

The advantages in planting corn early have been reported by several researchers (Pendleton and Egli, 1969; Shaw, 1977; Zuber, 1968). Efficient weed control and disease resistant seed varieties are encouraging farmers to plant early in the season when weather is permitting. In some years planting progresses very rapidly early in the season, later on heavy rains delay planting operations. It is advantageous to keep track of the percent planted by specific dates in order to determine if the current planting season is on schedule. The following phenological inputs have been tested during the development of the corn yield models:

PCTP20 = the percentage of corn planted by week 20,

PCTP21 = the percentage of corn planted by week 21, and

PCTNP = the percentage of corn not planted by week 21.

The harvesting date depends on the moisture content of corn and also on the prevalence of dry weather at harvest time. Heavy rains delay harvesting operations and yield losses due to dropped corn cobs or earworm damage are common (Zuber, 1968). The percentage of corn harvested by specific dates enable the modeler to account for any yield losses after maturity. The following variables have been tested during the development of the corn yield models:

H40 = the percentage of corn harvested by week 40,
H44 = the percentage of corn harvested by week 44, and
PCTNH = the percentage of corn not harvested by week 44.

F. Trend Removal

In an earlier study Eddy and Achutuni (1978) discussed fitting of linear and non-linear trend lines to corn and wheat yields. The non-linear trend developed earlier will now be tested on the Iowa and Illinois corn yield models. Further, corn yields are known to reflect the trend in nitrogen fertilizer usage over the years (Butell and Naive, 1978; McQuigg, 1975; Thompson, 1969). Nitrogen fertilizer application rates over the period 1969-1976 are also tested for trend removal.

F.1. Non-Linear Trend

In order to account for any leveling-off of corn yields in the near future, it is desirable to have a trend whose functional form will incorporate such changes in technological coefficients. Equations (23) to (27) that follow have been developed in an earlier study by Eddy and Achutuni (1978). The non-linear trend is given by:

$$\hat{y}_j = a_o + a_1 x_1 \exp(-a_2 x_2((t_j - a_3) - a_4 x_3)^2) \qquad (23)$$

where

$\hat{y}_j$ = the estimated yield in year j,
a_o = a constant,

a_j = the jth scaling factor required to keep all the decision variables in the same order of magnitude (j = 1, ..., 4),

t_j = the jth year of observation, and

x_1, x_2 and x_3 are the decision variables.

The procedure is to minimize the objective function:

$$\hat{\sigma}_R{}^2 = (1/N) \sum_{j=1}^{N} W_j((\hat{y}_j - a_o) - y_j{}^o)^2 \tag{24}$$

where

$\hat{\sigma}_R{}^2$ = the residual variance,

W_j = the weights which one can assign to give preferential treatment to certain parts of the data series,

$\hat{y}_j$ = the estimated yield in year j,

$y_j{}^o$ = the observed yield in year j,

a_o = a constant, and

N = the number of years for which data are available.

The maximum yield is modeled to occur in year t_{max}, where

$$t_{max} = a_3 + a_4 x_3 \tag{25}$$

The modeled maximum yield in year t_{max} is given by

$$Y_{max} = a_o + a_1 x_1 \tag{26}$$

The year when the maximum rate of increase in yield is modeled to occur is given by t_R, where

$$t_R = t_{max} - 1/(2a_2 x_2)^{\frac{1}{2}} \tag{27}$$

A non-linear programming (NLP) algorithm is used to minimize the objective function. It should be noted that the final decision variables are not, in their present form, maximum likelihood or unbiased estimates; therefore, the use of the non-linear trend is limited to forecasting crop yields into the near future.

F.2. Nitrogen Fertilizer Trend

As stated earlier, corn yields reflect the trend in nitrogen fertilizer usage over the years. The state level nitrogen fertilizer application rate is being considered as an alternate trend term. Crop district level fertilizer data are not available at the present; therefore, the macro-CRD models are based on state level fertilizer data. The intra-CRD variations in fertilizer usage are difficult to evaluate at this stage.

G. The Linear Regression Analysis Approach to Corn Yield Modeling

In this approach to corn yield modeling, several independent variables (representing time trend, cultural practices, weather and soil characteristics) are related to the dependent variable yield. The model coefficients are obtained using either multiple linear regression analysis or the stepwise regression procedure. Even though such a statistical approach does not explicitly treat the cause and effect relationships, Baier (1977) is of the opinion that it is a very practical approach to the prediction of crop yields. He further states that, the model coefficients and the validity of the estimates depend largely on the model design and representativeness of the input data.

According to McQuigg (1975), the three major sources of variability in yields of grain over a period of years are technological change, meteorological variability and random "noise." Technological change is the most important source of variability in yields. This includes increased fertilizer applications, improved management practices and pest control, and improved genetic qualities of seed. Meteorological variability within and between seasons is the second important source of variability in yields. "Random noise" is a combination of random influences that have not been included in the model. McQuigg (1975) concludes from his analysis of crop-yield data that, the technological component explains about 70 to 80 percent of the total variance about the sample mean, weather about 12 to 18 percent and "random noise" about 5 to 10 percent.

Technological variables are generally related to one another and model coefficients estimated from such data tend to be unstable. In an effort to minimize this problem of multicollinearity, a non-linear trend and applied nitrogen fertilizer are to be tested separately on the individual models. Proxy variables such as time are not included in this study in order to reduce the multicollinearity problem.

The meteorological variables are not truly independent because they are highly related through space and time (McQuigg, 1975). In this case, the multicollinearity problem can be minimized by not including in the analysis some of the variables that overlap in time. For example, if precipitation around silking (P_5) and the number of days precipitation exceeds three inches (P31) overlap in time then include the variable having a higher correlation with yield. Variables exhibiting autocorrelation will cause the model coefficients to be very unstable and often of the wrong algebraic sign.

The linear regression analysis approach to predicting crop yields for large areas is a practical one. The crop yield data as well as the meteorological data should be representative of the geographical region under consideration. Stability of the model coefficients will improve if the technological and meteorological variables are chosen so as to minimize the collinearity problem.

G.1. The Model

The general linear multiple regression model is given by:

$$y_i = \beta_1 x_{1i} + \beta_2 x_{2i} + \dots + \beta_m x_{mi} + \varepsilon_i \tag{28}$$

where

y_i = the observed yield during the ith year ($i = 1, 2, \dots, n$),

x_{1i} = 1 (the dummy variable),

x_{2i} = NLT_i (non-linear trend) or x_{2i} = NIT_i (nitrogen trend),

$x_{3i}, x_{4i}, \dots, x_{mi}$ = the phenological, meteorological and hydrological model inputs,

$\beta_1, \beta_2, \dots, \beta_m$ = the m model parameters to be estimated, and

ε_i = the residual error for the ith year.

The basic assumptions in the model represented by Equation (28) are:

1) ε_i is a random variable with mean zero and variance σ^2 (unknown), that is, $E(\varepsilon_i) = 0$, $V(\varepsilon_i) = \sigma^2$; and $\varepsilon_i \sim N(0, \sigma^2)$.

2) ε_i and ε_j are uncorrelated, $i \neq j$, so that $COV(\varepsilon_i, \varepsilon_j) = 0$.

Therefore

$$E(y_i) = \beta_1 + \beta_2 x_{2i} + \dots + \beta_m x_{mi}$$

$$V(y_i) = \sigma^2$$

$$E((y_i - \bar{y})(y_j - \bar{y})) = 0$$

In matrix notation Equation (28) reduces to

$$Y = X\beta + \varepsilon \tag{29}$$

Note that:

Y is an n by 1 vector,

X is an n by m matrix,

β is an m by 1 vector and

ε is an n by 1 vector.

The predicted yield $\hat{Y}$ is given by:

$$\hat{Y} = X\hat{\beta} \tag{30}$$

where

$\hat{Y}$ is an n by 1 vector and

$\hat{\beta}' = (\hat{\beta}_1, \hat{\beta}_2, \ldots, \hat{\beta}_m)$, the least square estimates of β.

The model parameters are to be estimated using either a stepwise screening regression procedure or the multiple linear regression analysis procedure. The stepwise screening procedure models are not guaranteed to represent real-world processes very accurately; therefore, models based on physiological reasoning and known climate-yield relationships will be tested using the multiple linear regression analysis procedure with preselected variables.

The stepwise screening procedure finds the first single variable model which produces the highest R^2 statistic. R^2 is the square of the multiple correlation coefficient; it is also expressed as the ratio of the regression sum of squares to the corrected total sum of squares. For each of the other independent variables an F-statistic reflecting that variable's contribution to the model were it to be included in the model is computed. If the F-statistic for any of the other variables produces a significance probability greater than the specified significance level for entry, then the variable producing the largest F-statistic is included in the model. After a variable has been added the stepwise procedure computes a partial F-statistic for all the variables in the model. Any variable not meeting the specified F-value for staying in the model is then deleted. The process terminates when no other variables meet the conditions for entry into the model or when the variable to be added to the model is the one just deleted from it. (For a detailed computational procedure refer to Draper and Smith, 1966).

The multiple linear regression analysis procedure includes all the variables specified in the model, while computing the model parameters. It does not guarantee that all the variables meet any specified significance level for staying in the model. That is, not all variables in the model may be significant. This procedure is very useful for testing models based on physiological reasoning and known climate-yield relationships.

The state and macro-CRD level models for this study retain the general form of Equation (29); stepwise screening and multiple linear regression techniques will be used to obtain the individual predictive equations represented by the general form of Equation (30).

In this study there are two model truncations, the first after planting and the second after silking. Truncated models are obtained by computing the model coefficients using only those variables that precede the truncation period. This procedure is repeated for each of the truncations. Truncated models enable the modeler to estimate crop yield at successive stages of crop development; also any yield reductions due to the known occurrence of random events such epidemics of crop disease or pest infestations can be incorporated in the model as the growing season progresses.

G.2. Examining the Regression Equation

There are several criteria by which a given model may be judged for its statistical reliability. Two such criteria, the coefficient of determination and signal to noise ratio are used in this study.

The coefficient of determination (R^2). The coefficient of determination is a measure of the percent variation in yield explained by the variables in a model. According to Draper and Smith (1966), the coefficient of determination is given by:

$$R^2 = \sum_{i=1}^{n} (\hat{y}_i - \bar{y})^2 / \sum_{i=1}^{n} (y_i - \bar{y})^2 \qquad (31)$$

where

y_i = the observed yield during the ith year,

$\hat{y}_i$ = the predicted yield for the ith year,

$\bar{y}$ = the overall mean yield, and

n = the number years.

R^2 is generally expressed as a percentage. In matrix notation

$$R^2 = (\hat{\beta}'X'Y - n\bar{Y}^2)/(Y'Y - n\bar{Y}^2) \qquad (32)$$

where $\hat{\beta}' = (\hat{\beta}_1, \hat{\beta}_2, \ldots, \hat{\beta}_m)$.

It should be recognized that R^2 can be made unity simply by employing m properly selected coefficients in the model. According to Sakamoto (1977), the predictive precision of a model is more important than a high R^2 value. He suggests that confidence limits on the predicted yields can be used to compare the predictive ability of different models.

Signal to noise ratio. In crop-weather models the technological variables explain about 70 to 80 percent of the total variation about the mean yield. Therefore, this variance has to be subtracted from the total variance in order to study the model variance attributable to the weather and random components. The coefficient of variation does not separate the technological and weather influences, therefore high R^2 values can be obtained by including a good trend term in the analysis. A "good" climate/yield model is one that attributes a high percentage of the total variance remaining after trend removal to weather components alone. The "signal to noise ratio" is one such measure and is discussed below.

$$\frac{S}{N} = \{(\hat{\beta}'X'Y-n\overline{Y}^2)-SS(T)\}/(Y'Y-\hat{\beta}'X'Y) \qquad (33)$$

where

S = the signal (terms in the numerator),

N = the noise (terms in the denominator),

$(\hat{\beta}'X'Y-n\overline{Y}^2)$ = sum of squares due to regression,

$SS(T)$ = sum of squares due to technological variables, and

$(Y'Y-\hat{\beta}'X'Y)$ = residual variance.

Large values of S/N ratio indicate a model with significant weather effects; relatively low ratios indicate a weather insensitive model. Note that by virtue of Equations (32) and (33) two models may have the same R^2 values but different S/N ratios.

H. Model Testing and Sensitivity Analysis Procedures

Standard bootstrap and jackknife methods of model testing are to be used in this study. The data for the years 1974-1976 will be used to make independent tests on the individual models. Sensitivity analysis procedures on yield estimates based on regression coefficient uncertainties are also presented.

H.1. Model Testing

The models will be tested using the standard bootstrap and jackknife techniques. The bootstrap procedure consists of computing the regression coefficients using data from year k_1 through k_m to predict the yield for year k_{m+1}. Recompute the coefficients after including year k_{m+1} to predict the yield for year k_{m+2} and so on.

The jackknife procedure consists of leaving out a single year k_i (where $k_1 < k_i < k_m$), computing the coefficients, and then predicting the yield for year k_i. The process is repeated by leaving out the year k_{i+1} and so on.

Meteorological and phenological data for the years 1974-1976 will be used to make independent tests on the models. First, the model coefficients are estimated from the 1949-1973 data; and then the 1974-1976 yield estimates are made making use of the above coefficients and the corresponding year's data.

H.2. Sensitivity Analysis

Crop yield models which use linear regression are subject to a variety of problems.

1) The predictor variables are often non-homogeneous (blight years and variety changes are examples).

2) The sample size is small and auto-correlation in the variables makes it even more non-representative.

3) Multicollinearity among variables can produce unstable coefficients.

4) The model form itself is inadequate. (Non-linear interactions between soil moisture and fertilizer and changes in cultural

practice are examples of variables not included.

The objective of the sensitivity analysis is to study the model response to uncertainties in the regression coefficients as well as the weather variables. The procedure outlined in this section is based on an earlier study by Eddy (1978).

Consider the prediction Equation (29) for $\hat{Y}$. The variance-covariance matrix of the vector $\hat{\beta}$ is by:

$$V(\hat{\beta}) = (X'X)^{-1}\sigma^2 \tag{34}$$

where σ^2 = the residual variance.

Let X_k be a selected vector of X. The predicted value of Y for this value of X is $\hat{Y}_k$, and its variance is given by:

$$\mathrm{var}(\hat{Y}_k) = X_k(X'X)^{-1}X_k' \; \sigma^2 \tag{35}$$

where σ^2 is estimated by $\hat{\sigma}^2$, and

$$\hat{\sigma}^2 = \left(\sum_{i=1}^{n} (Y-\hat{Y})^2\right)/(n-m) = \tag{36}$$

$$(Y'Y-Y'X(X'X)^{-1}X'Y)/(n-m)$$

It can be seen from Equation (35) that the variance of $\hat{Y}_k$ is a function of the particular observation vector X_k. Therefore, under unfavorable weather conditions the yield estimate would be lower than normal, but the uncertainty of this estimate could be higher than average.

A mean variance of the yield estimate over a selected set of predictor variables is given by:

$$\overline{\sigma^2(\hat{y})} = \{\sum_X f(X)\cdot \mathrm{var}(\hat{Y}|x)\}/\{\sum_X f(X)\} \tag{37}$$

One can model the weights (f(X)) using the function

$$f(X) = f(X_2, X_3, \ldots, X_m) = \{1/(2\pi)^{m/2}|\mathrm{cov}\; X|^{-1/2}\}\cdot \tag{38}$$

$$\exp\{-(X-\mu)^t(\mathrm{cov}\; X)^{-1}(x-\mu)/2\}$$

where μ = the (m-1 by 1) vector of expected values for the predictors.

The average variance of Y over a complete set of weather variables can be obtained from Equations (35), (36) and (37) to get:

$$\mathrm{var}(\hat{y}) \approx \frac{\sum_{\mathrm{all}X_k} X_k(X'X)^{-1}X_k \exp\{-(X_k'-\mu)'(\mathrm{cov}\ X)^{-1}(X_k-\mu)/2\}}{\sum_{\mathrm{all}X_k} \exp\{-(X_k-\mu)'(\mathrm{cov}\ X)^{-1}(X_k-\mu)/2\}} \quad \hat{\sigma}^2 \tag{39}$$

where X_k is an m-1 by 1 vector.

Note that the regression coefficients do not appear explicitly on the right hand side of Equation (39); in fact, the predictand appears through $\hat{\sigma}^2$ (also refer to Equation (36)). This gives an opportunity to study the uncertainty in yield estimates as a function of runs of weather variables (Eddy, 1978). One can study from the following points of view:

1) using μ and cov X for a long-term series (for example 1901-1973),

2) using μ and cov X for a particular decade (such as 1931-1940),

3) making a climate change hypothesis about the climate variables, or

4) making hyptheses concerning the interaction between the weather and fertilizer variables.

According to Eddy (1978), such examinations would proceed by:

1) picking a model and calculating the Y'X, X'X and μ_x matrices for the dependent (and complete) data set in order to establish benchmark values for $\hat{\sigma}^2$ and $\overline{\sigma^2(\hat{Y})}$,

2) selecting subsets of the predictor variables from the dependent data sample to study the consequent changes in $\hat{\sigma}^2$ and $\overline{\sigma^2(\hat{Y})}$,

3) varying μ_x and σ_x^{2}, calculating the required changes in Y'X and X'X and the implied changes under assumptions in $\hat{\sigma}^2$ and $\sigma(\hat{Y})^2$, and

4) modeling some of the correlation coefficients implied in Y'X and X'X.

It was found by Eddy (1978) that any perturbations introduced into the model, by changing σ_x^{2}, can lead to a considerable increase in the uncertainty of the yield estimate (larger $\sigma^2(\hat{Y})$) and residual variance ($\hat{\sigma}^2$). In another test the uncertainty in the yield estimate was also increased when the correlation coefficient between nitrogen fertilizer and soil moisture during silking was increased two-fold. However, the uncertainty in the yield estimate improved when the two variables were assumed to be uncorrelated. Finally, the influence of climate variation on model stability and predicted mean yield were also studied by using different mean values for the weather variables corresponding to each decade of interest. According to Eddy (1978), yield variations under present technology would have varied because of weather alone by as much as 10 percent over the past seventy-five years.

CHAPTER IV

RESULTS AND DISCUSSION

In this chapter results from the current study are presented and discussed in detail. The first section deals with the time series of phenological, yield and fertilizer data for Iowa and Illinois corn. A non-linear time trend is also fitted to the time series of corn yields. In the second section, the multiple linear regression and the stepwise procedure models for the individual macro-CRDs and states are presented and discussed in detail. Results from model testing using the jackknife, bootstrap and independent tests are presented in the third section. The truncated model testing results are discussed in the fourth section. In the last section, results from the sensitivity analyses on the individual models are presented and discussed in some detail.

A. Time Series of Phenology, Yield and Fertilizer Data

The phenological time series for Iowa and Illinois states are shown plotted in Figures 5 and 6. On the average corn is planted by week 20 in both the states, silking and maturity take place a week earlier in Iowa, whereas harvesting is delayed by one week. The silking and maturity curves are seen to be generally reflecting the fluctuations in the observed planting weeks. Delays in harvesting are generally weather

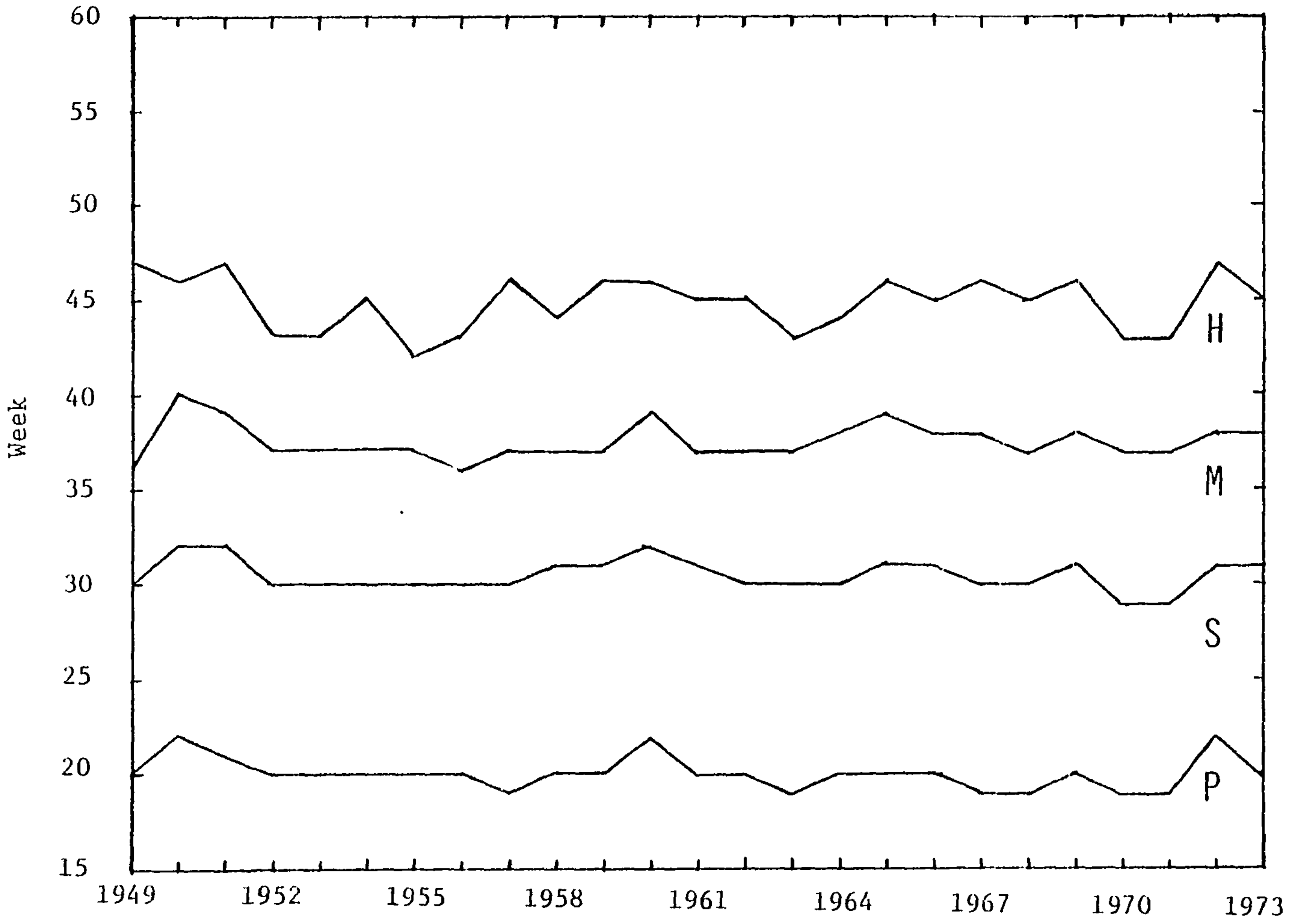

Figure 5. Observed Week of Occurrence of Phenological Stages for Corn in Iowa. (P = Planting, S = Silking, M = Maturity and H = Harvesting.)

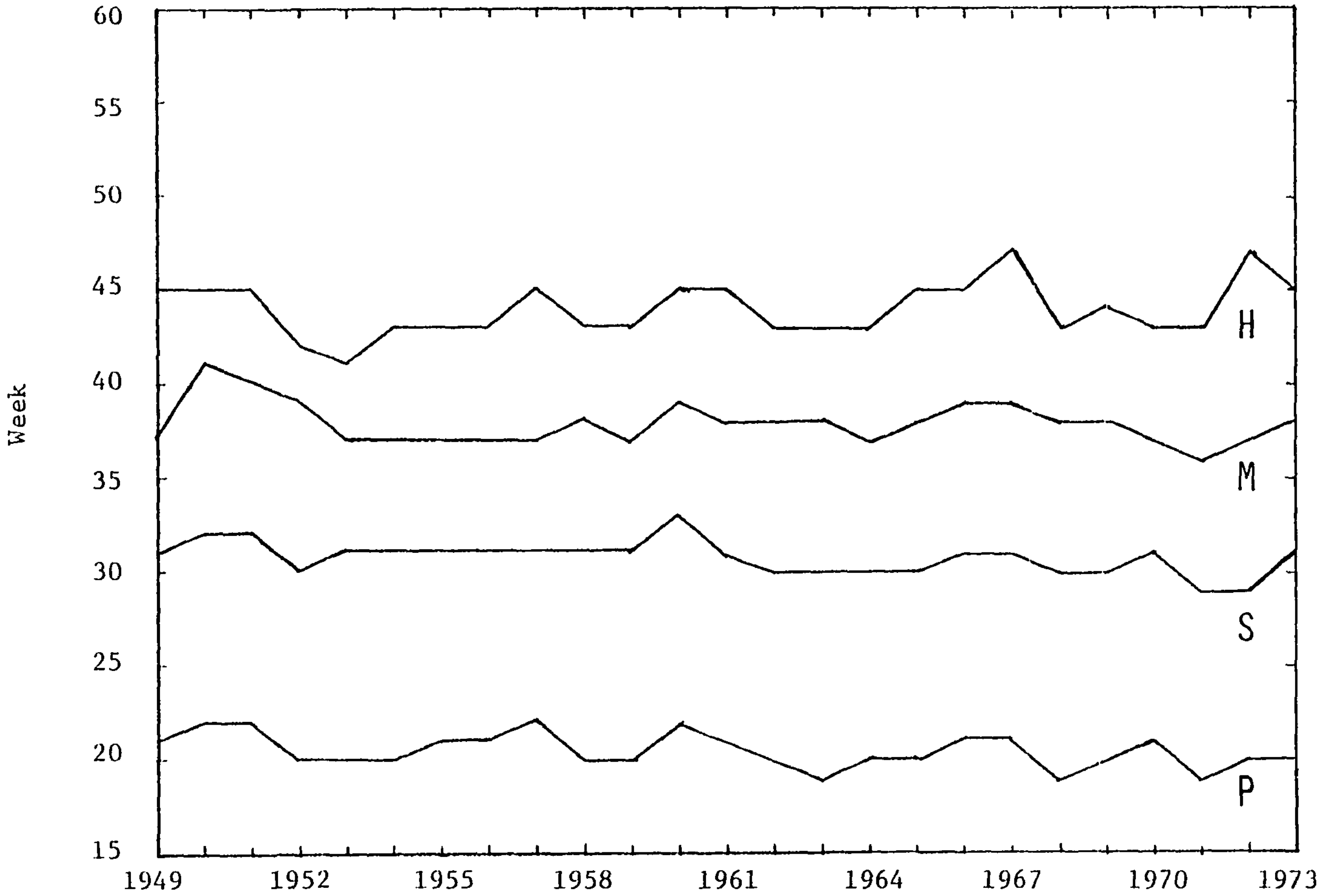

Figure 6. Observed Week of Occurrence of Phenological Stages for Corn in Illinois. (P = Planting, S = Silking, M = Maturity and H = Harvesting.)

related and so the time series show larger annual fluctuations than for any other stage.

In Iowa planting was significantly delayed in 1950, 1960 and 1972. The silking and maturity stages were also delayed in the same years; however, harvesting was also delayed during 1972.

In Illinois planting has never been delayed beyond two weeks from the long time mean. A delay of two weeks in planting occurred in 1950, 1951. 1957 and 1960; note that harvesting was also delayed in 1951. It should be pointed out that farmers tend to plant late maturing varieties whenever weather is favorable for early plantings and vice-versa. Varietal information is required in order to determine how delays in maturity are related to weather and different maturity ratings of the seed.

The time series of corn yields and the non-linear trend for the individual macro-CRDs and states are shown in Figures 7 through 13. In 1970, the southern corn leaf blight destroyed the crop substantially and so the average of yield for 1969 and 1971 has been used in the trend analysis. Nitrogen fertilizer application rates are shown plotted for the individual state alone. The non-linear trend model coefficients and statistics are given in Table 9. The table shows that the maximum rate of increase in yield occurs around 1958 in Iowa and Illinois. The trend shows that corn yields are likely to level off around 1982. Corn yields in Illinois have a smaller variation around the trend line than in Iowa. The model projections have to be interpreted with caution and should not be used for long-range forecasts as technology is rapidly changing. The model coefficients have to be recomputed for each additional year of data.

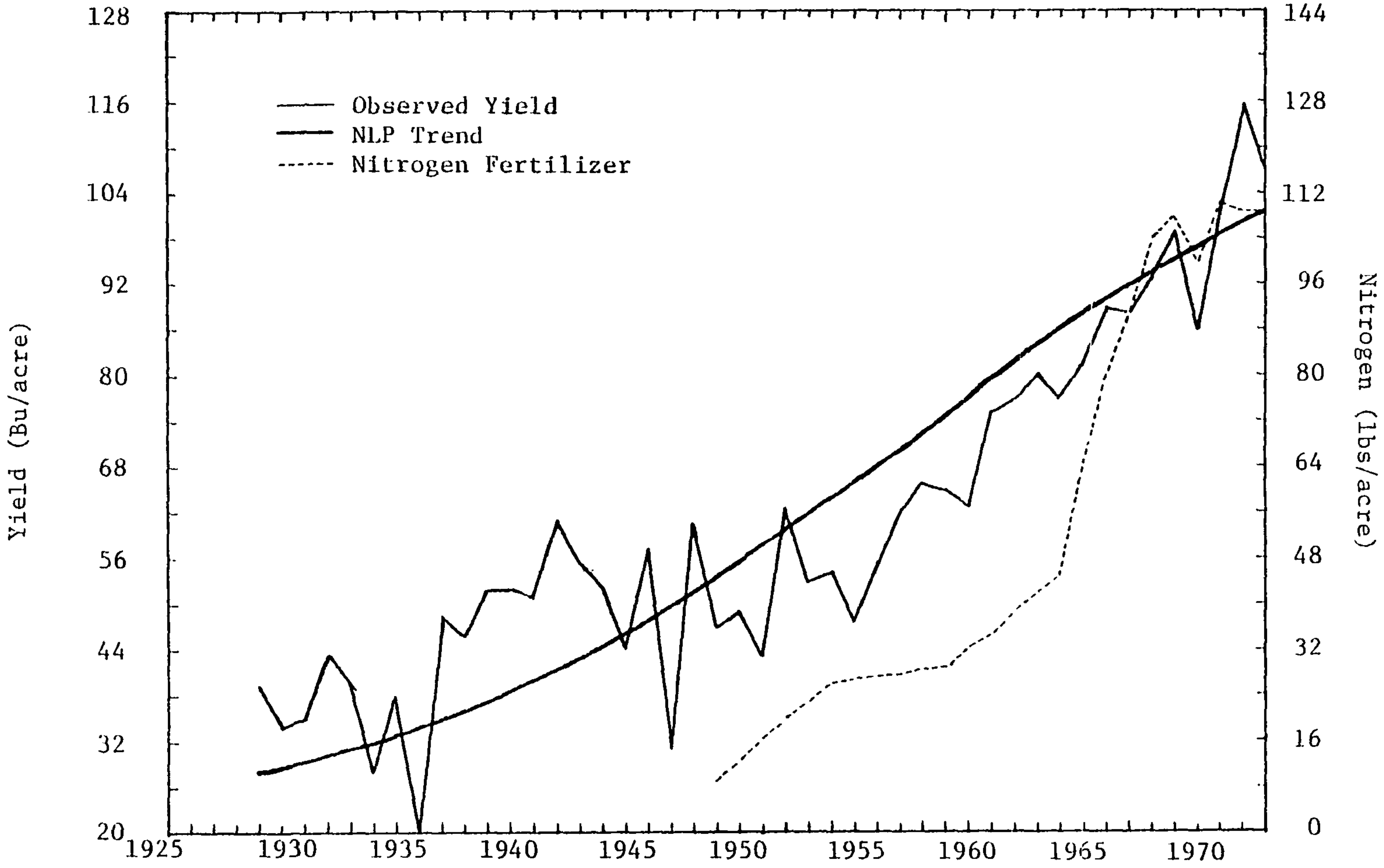

Figure 7. Iowa State Corn Yields, Non-Linear Trend Line and Nitrogen Fertilizer Usage.

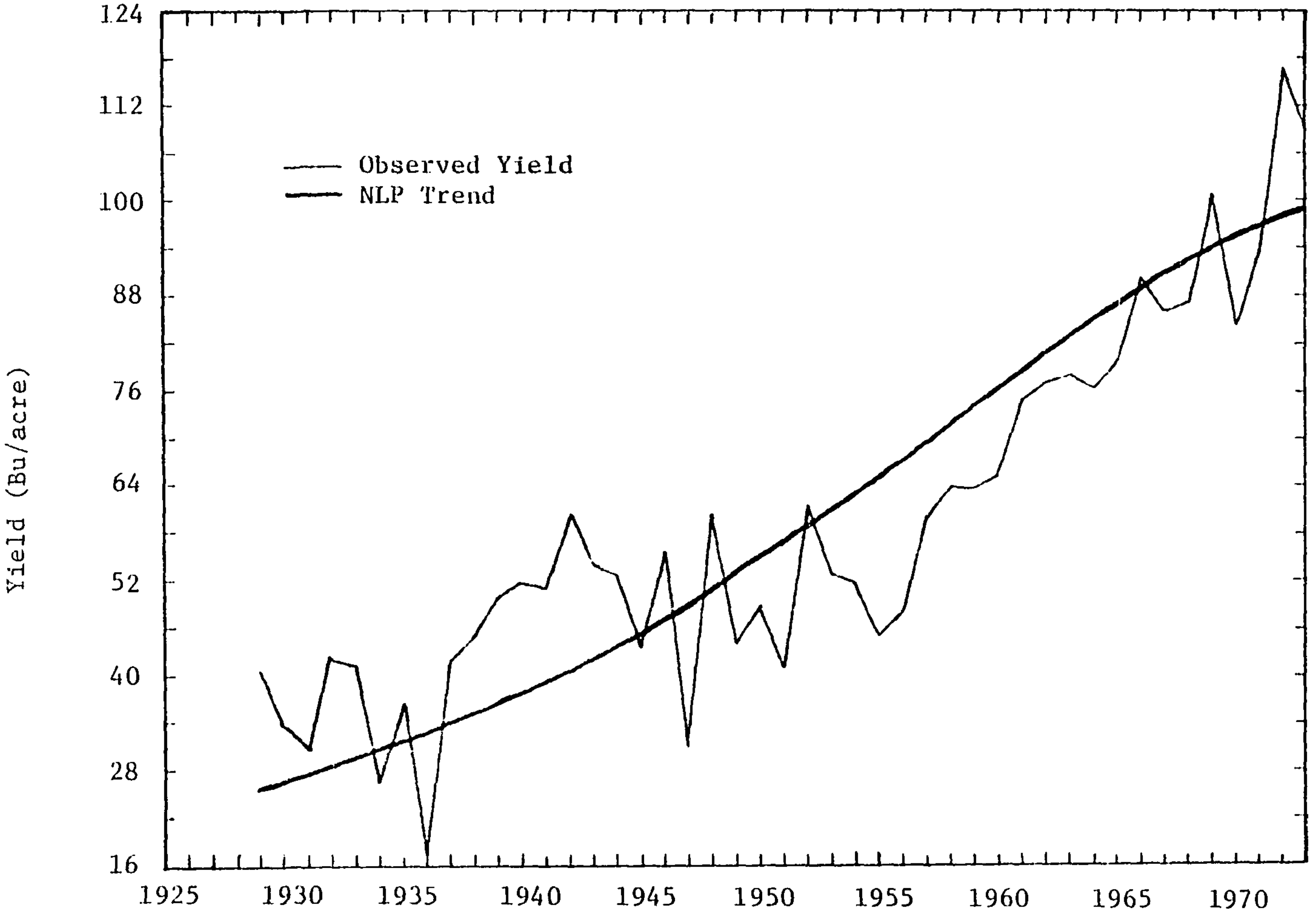

Figure 8. Corn Yields for Iowa-West Macro-CRD and Non-Linear Trend Fit.

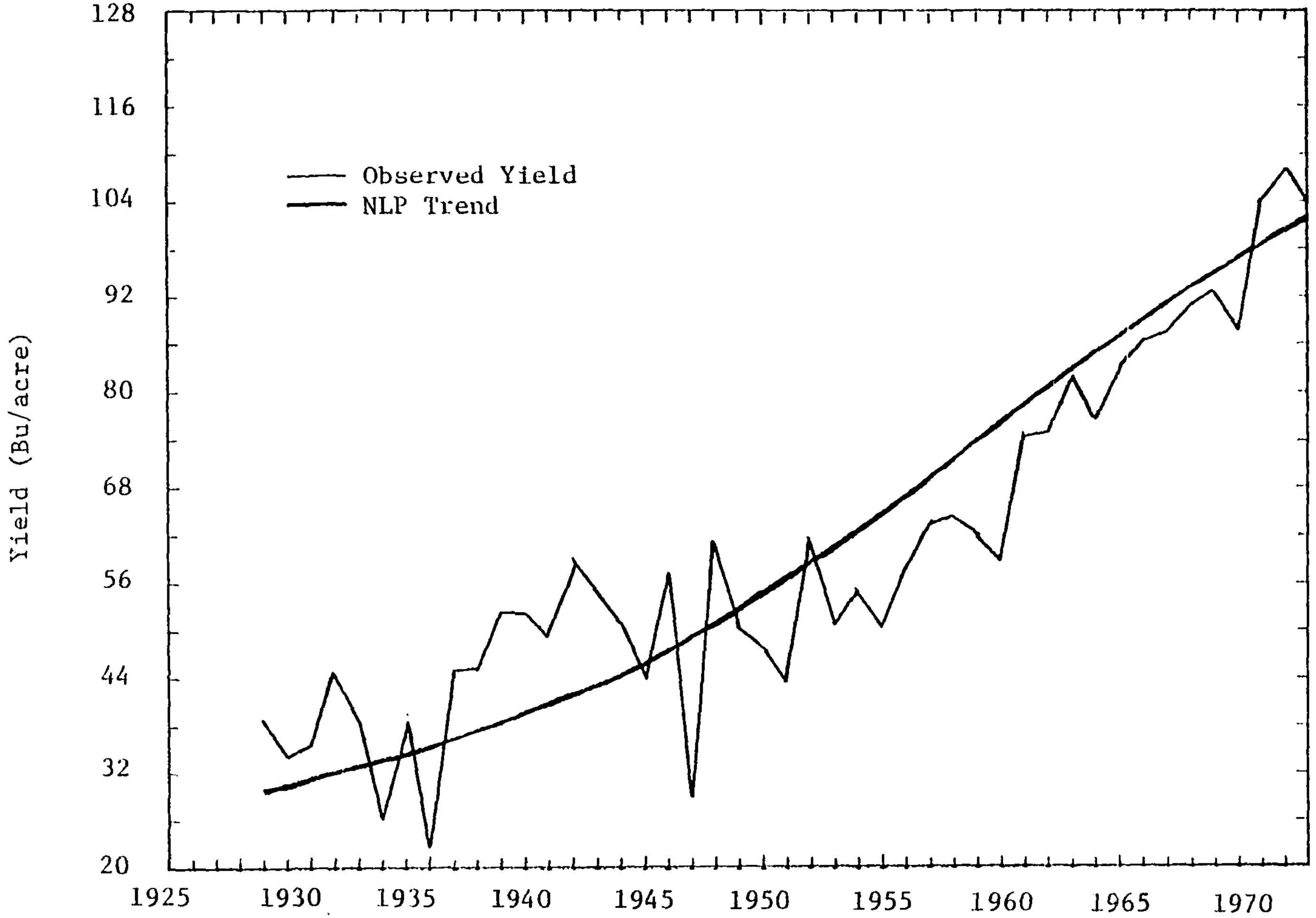

Figure 9. Corn Yields for Iowa-East Macro-CRD and Non-Linear Trend Fit.

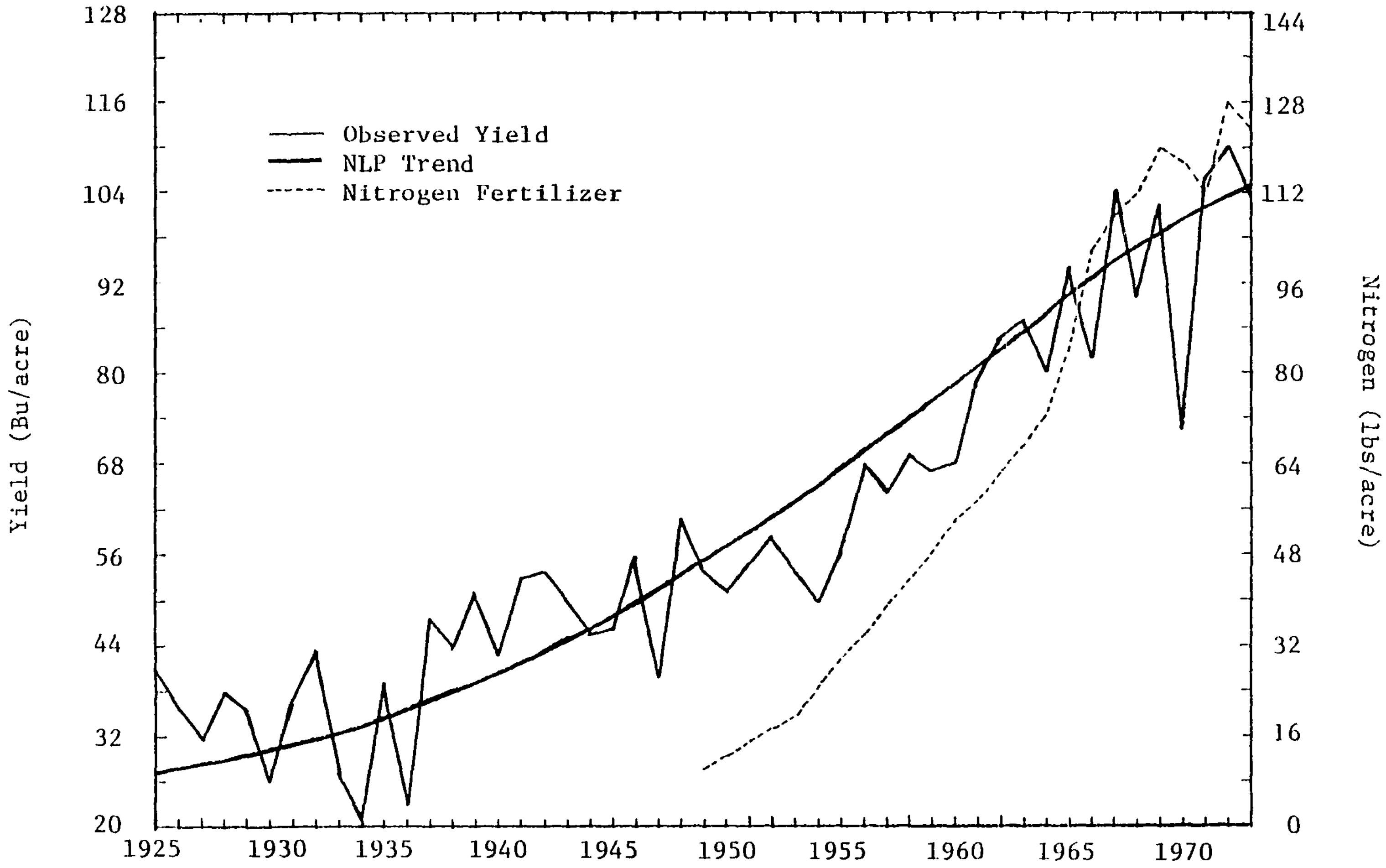

Figure 10. Illinois State Corn Yields, Non-Linear Trend Fit and Nitrogen Fertilizer Usage.

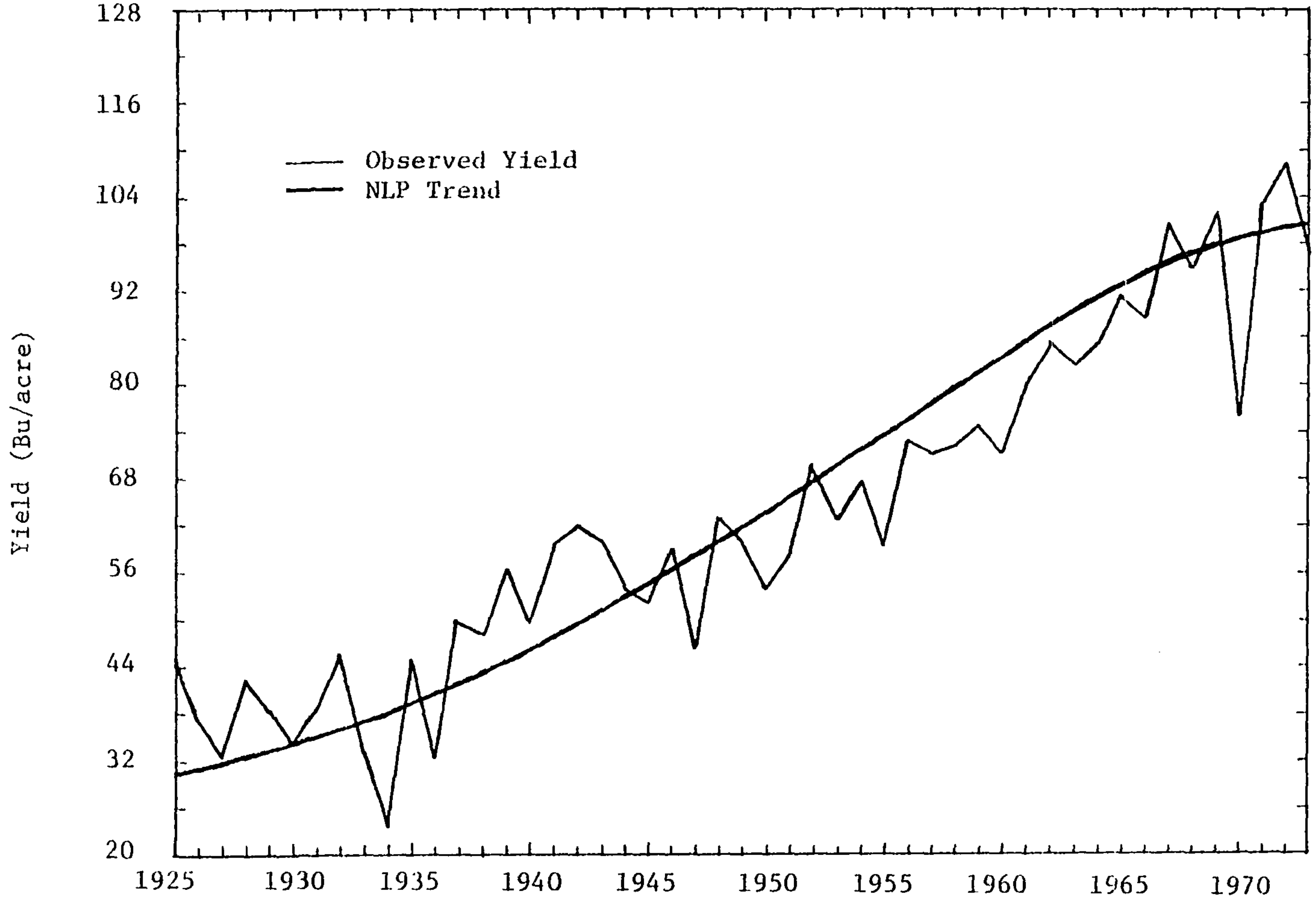

Figure 11. Corn Yields for Illinois-North Macro-CRD and Non-Linear Trend Fit.

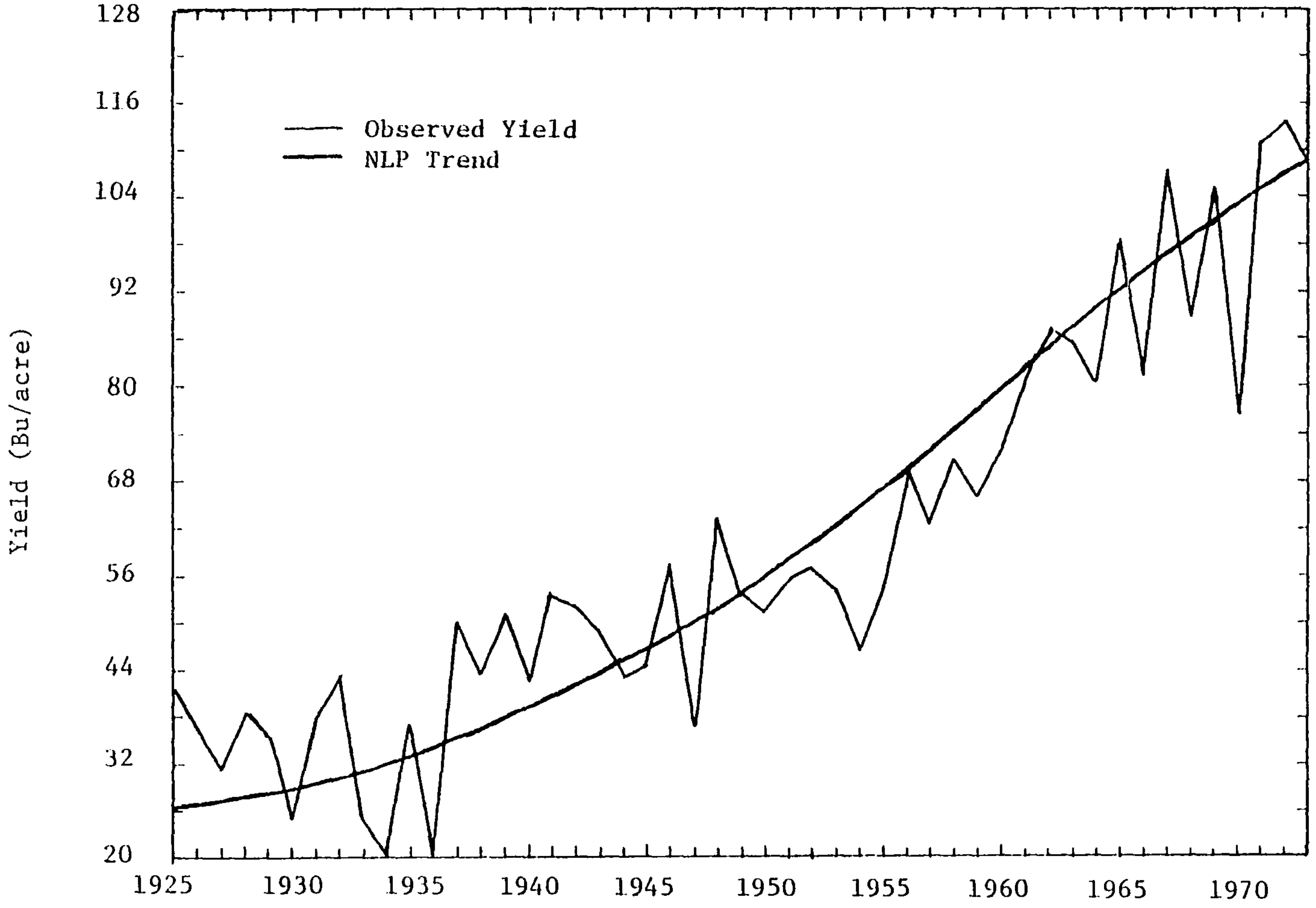

Figure 12. Corn Yields for Illinois-Central Macro-CRD and Non-Linear Trend Fit.

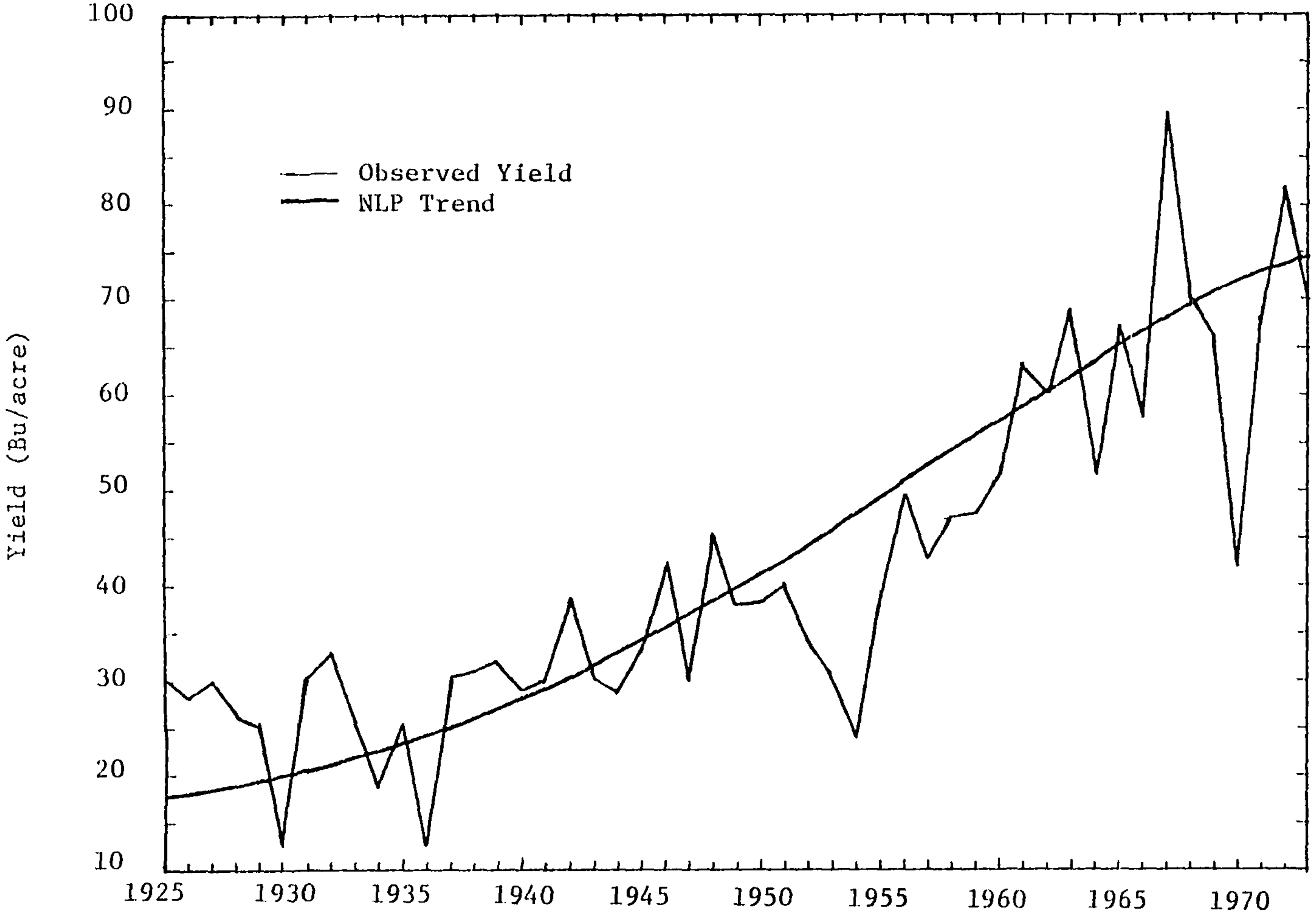

Figure 13. Corn Yields for Illinois-South Macro-CRD and Non-Linear Trend Fit.

Region	a_o	a_1	a_2	a_3	a_4	X_1	X_2	X_3	t_{max}	y_{max}	t_r	RMS (Obs-Trend)
<u>Iowa</u>												
West	98.98	-.001	.001	54.0	.001	.86	.90	.98	1981	102.23	1957	10.42
East	91.00	-.001	.001	57.0	.001	.94	.90	.98	1984	108.16	1960	9.05
State	96.00	-.001	.001	49.0	.001	.90	.90	1.09	1982	105.93	1958	9.74
<u>Illinois</u>												
North	84.45	-.001	.001	55.0	.001	.92	.90	.97	1978	101.05	1954	7.17
Central	92.98	-.001	.001	54.0	.001	1.02	.90	1.09	1983	115.90	1959	8.73
South	77.45	-.001	.001	54.0	.001	.83	.90	1.06	1981	76.72	1957	8.26
State	88.50	-.001	.001	55.0	.001	1.00	.90	1.06	1982	110.13	1958	7.86

Table 9. Non-Linear Trend Characteristics for Iowa and Illinois Corn

The Iowa state and macro-CRD yield time series reveal low yields until the mid-thirties, yields from 1937 to 1955 show the influence of changing technology. The period 1956 to 1973 characterizes a rapid increase in corn yields attributable to increased fertilizer usage, better cultural practices, improved seed varieties, effective pesticides and herbicides (McQuigg, 1975). An interesting feature of the state fertilizer usage (Figure 7) is that between 1964 and 1969 Iowa farmers increased nitrogen application on an average annual rate of nearly 12 pounds per acre realizing only an average increase in yields of 4.5 bushels per acre. It should be realized that this increase in yield falls within the variability in yield due to weather. Another possibility is that the farmers may be over-fertilizing the crop. Corn yields in Iowa-West are somewhat higher than in Iowa-East possibly due to supplemental irrigation. The non-linear trend analyses show the 1960's to be slightly below the trend because of the low yields prior to 1955.

In Illinois farmers have been steadily increasing their nitrogen application rates from 1954 onwards. The average annual rate of increase during the 1964-1969 period is about 9.6 pounds per acre and the farmers realized an average increase of nearly 5 bushels per acre. Again, the increase can be easily offset by adverse weather during the growing season. Corn yields will increase whenever favorable weather complements the present fertilizer application rates.

The non-linear trend line does a much better job during the 1960's in Illinois state and macro-CRDs than in Iowa. The northern and central macro-CRDs yield much higher than the southern one. There is not much irrigation in this drier southern region.

B. Iowa-Illinois State and Macro-CRD Models

B.1. Iowa State Corn Models

The multiple linear regression model developed in this study for Iowa state is:

$$\hat{y} = b_o + b_1NIT + b_2PWK + b_3P_3Q + b_4P_5T90 + b_5R_{45} \qquad (40)$$

$$= 74.63 + .54NIT - 1.35PWK + 1.29P_3Q + .30P_5T90 - .80R_{45}$$

(.8841) (.0001) (.0132) (.0292) (.0012)

(.0001) (.4100) (.1719) (.0277) (.5674)

$R^2 = 92.77\%$ $S/N = .60$ $\gamma = 37.65\%$

where

the first row of numbers in parentheses indicate the fraction of total variance explained by the corresponding variable,

the second row of numbers in parentheses indicate the probability ($Pr > |t|$) that the model parameter is zero (based on a 't' - test at $\alpha = .05$). Probabilities in excess of .05 mean that the corresponding model variable is insignificant (Note: the above two conventions will be used in the rest of this section).

R^2 = the coefficient of determination,

S/N = the signal to noise ratio and

$\gamma = S*100/(S + N)$, the percent of variation remaining after removal of trend, explained by weather.

In Equation (40) the nitrogen trend term is highly significant and explains 88 percent of the total variation about the mean yield. The observed week of planting (PWK) is included to account for any yield losses due to delayed plantings. This term is not very significant because planting was not significantly delayed during the 1949-1973 period. However, drastic yield reductions in 1974 due to extreme delay in planting, indicate the importance of this term. Precipitation during the early vegetative stage is either beneficial or detrimental to yields, depending on the moisture reserves. Therefore the quadratic term for precipitation (P_3Q) has been included. The interaction term (P_5T90) accounts for the non-linear interaction between precipitation around silking and temperature in excess of 90°F. Wet weather around harvest time is known to reduce yield (Shaw, 1977). The last term (R_{45}) accounts for such reductions in yield. The model has an R^2 of 93 percent and the weather variables explain 37.65 percent of the variation remaining after the trend has been removed.

In the stepwise regression model developed in this study, all the variables are significant at the $\alpha = .05$ level (second row in parentheses is therefore omitted), and is given by:

$$\begin{aligned} \hat{y} &= b_o + b_1 NIT + b_2 P_5 T90 \qquad (41) \\ &= 47.90 + .52NIT + .33P_5T90 \\ &\qquad\qquad (.8850) \quad (.0328) \\ R^2 &= 91.78\% \quad S/N = 0.40 \quad \gamma = 28.52\% \end{aligned}$$

The stepwise model is based on only 24 years of data and therefore may not be representative of the climatology of the region. Anomalous weather influences not characteristic of the data set may offset the predictive ability of the model. The difference in R^2 values between the two models is only 0.0099 percent however. The weather variables in the multiple regression model explain an extra 8.86 percent of the variance remaining after trend removal, over the stepwise model. In other words, the multiple regression model is more sensitive to weather.

According to Draper and Smith (1966), the 95 percent confidence limits for the true mean values of Y at X_k are given by:

$$C.L = \hat{Y} \pm t\{(n-m-1), 0.975\} \hat{\sigma} \{X_k'(X'X)^{-1} X_k\}^{1/2} \quad (42)$$

where

$t\{(n-m-1), 0.975\}$ = 97.5 percentile 't' value for (n-m-1) degrees of freedom,

n = the number of years of data,

m = the number of independent variables in the model, and

$\hat{\sigma}$ = the estimated standard deviation of residuals.

The smaller the confidence limits, the greater is the accuracy in estimating the true mean yield for any particular year. Generally, the confidence limits established by the stepwise procedure are smaller than those established by the multiple linear regression approach. According to Draper and Smith (1966), data points not typical of the rest of the data give rise to large model residuals called "outliers;" these outliers lie about three or four standard deviations or further from the mean of the residuals. Corn yields for 1970, the corn blight year, have not been included in the analyses for this reason. The observed and predicted yields for the two state models and the 95 percent confidence limits are shown in Figures 14 and 15, respectively.

During 1950 and 1951, heavy rains delayed planting operations by nearly two weeks, there were also heavy rains during the early vegetative stage. Both these factors contributed to reduced yields. The stepwise model (lacking the PWK and P_3Q terms) shows larger residuals for these two years. Both the models are underestimating yield during favorable years. During 1968 and 1969, applied nitrogen usage increased considerably (reference Figure 7), and both the models reflected this change.

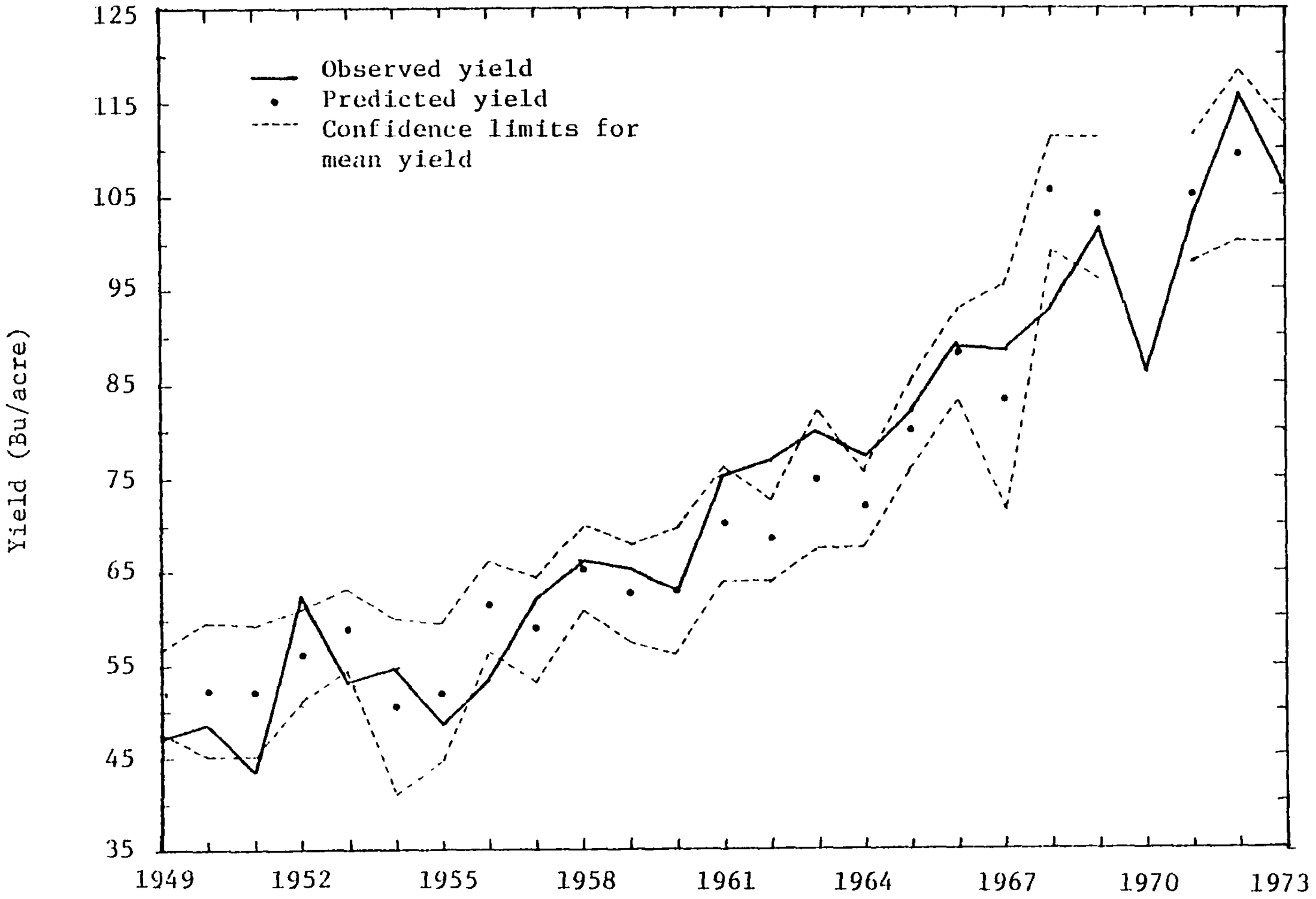

Figure 14. Observed and Predicted Corn Yields for Iowa State using the Multiple Regression Model. The Blight Year (1970) is excluded from the Analysis.

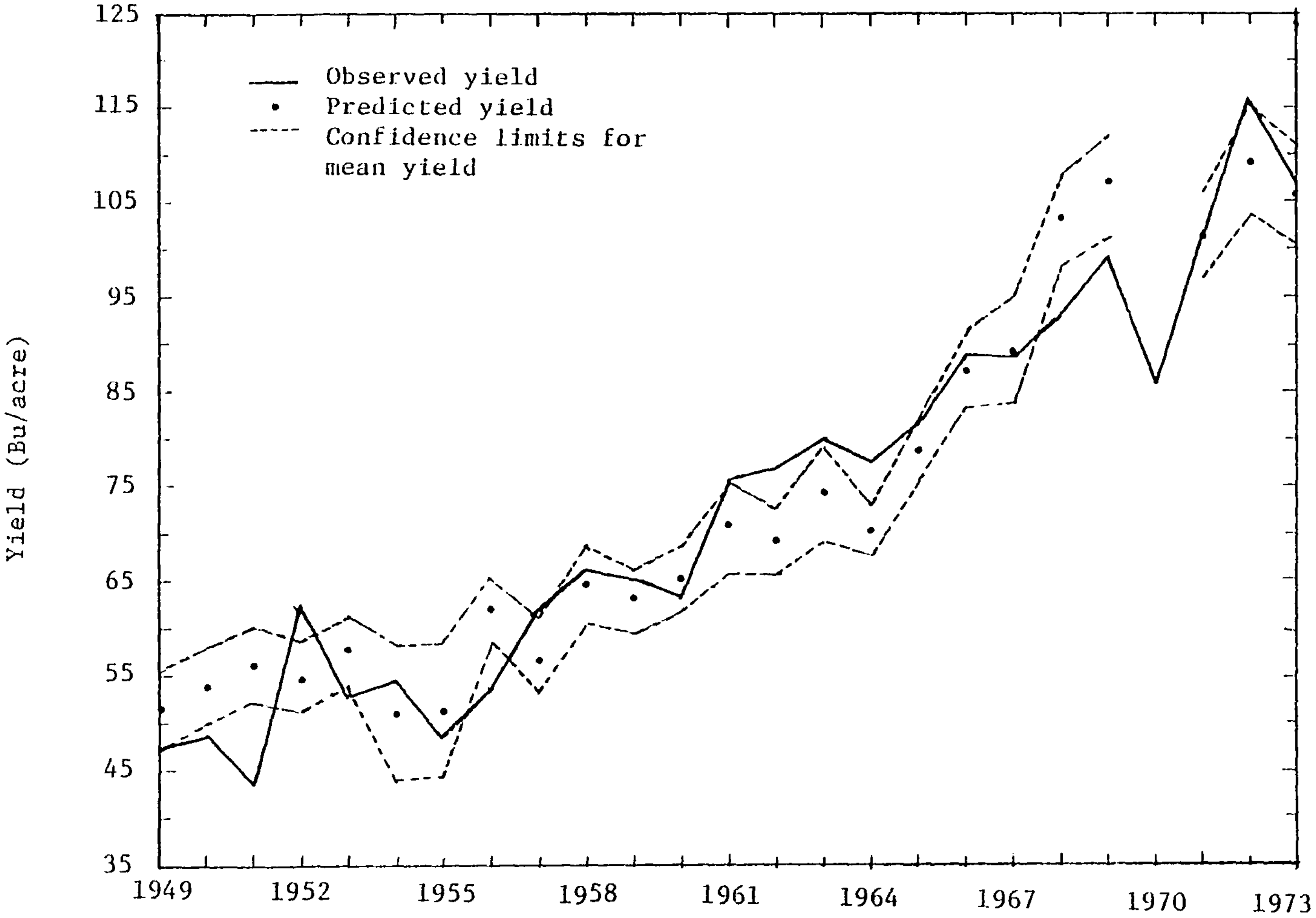

Figure 15. Observed and Predicted Corn Yields for Iowa State using the Stepwise Regression Model. The Blight Year (1970) is excluded from the Analysis.

However, the stepwise model does not have enough weather inputs to account for subsequent yield reductions and so leads to large residuals.

B.2. Iowa Macro-CRD Models

The Iowa-West multiple regression model has been developed in this study from several test models and is given by:

$$\hat{y} = b_o + b_1NIT + b_2SM3 + b_3P_3Q + b_4R_3 \qquad (43)$$

$$= 22.32 + .56NIT + .71SM3 + 1.31P_3Q - .08R_3$$

$$(.8754) \quad (.0295) \quad (.0097) \quad (.0006)$$

$$(.0001) \quad (.0298) \quad (.1457) \quad (.7280)$$

$$R^2 = 91.53\% \quad S/N = .47 \quad \gamma = 32.02\%$$

Nitrogen fertilizer explains about 88 percent of the total variation. Soil moisture around silking time (SM3) is significant and explains nearly 3 percent of the variation. P_3Q and R_3 have been included to account for precipitation influences during the early vegetative stage and little after maturity, respectively. Temperature stress around silking was not significant even in the other models that were tested. Probably, timely showers during this period may be relieving some of the temperature stress. The overall model has an R^2 of 91.53 percent and the residual variance is 8.5 percent. About 32 percent of the variance remaining after trend removal is explained by the weather variables.

The equation for the Iowa-West stepwise model developed in this study is given by:

$$\hat{y} = b_o + b_1NIT + b_2SM3 + b_3P_3Q + b_4P_4 \qquad (44)$$

$$= 22.95 + 0.56NIT + 0.90SM3 + 1.51P_3Q - 3.22P_4$$

$$(.8754) \quad (.0295) \quad (.0097) \quad (.0164)$$

$$R^2 = 93.11\% \quad S/N = .81 \quad \gamma = 44.7\%$$

The nitrogen fertilizer term explains 87.5 percent of the total variance. Soil moisture around tasseling silking and pollination (SM3) explains nearly 3 percent of the total variance. P_3Q is a quadratic term for P_3 and accounts for the non-linear relationship between precipitation during the early vegetative stage and corn yields. P_4 is the precipitation during four to three weeks prior to silking, the coefficient has a negative sign indicating heavy precipitation at this time is associated with lower yields.

The equation for the Iowa-East multiple linear regression model developed in this study is given by:

$$\hat{y} = b_o + b_1NIT + b_2PWK + b_3P_3Q + b_4P_5T90 + b_5R_{45} \qquad (45)$$

$$= 116.68 + 0.51NIT - 3.3PWK + 2.21P_3Q + 0.32P_5T90 - 1.74R_{45}$$

$$(.8727) \quad (.0021) \quad (.0112) \quad (.0457) \quad (.0080)$$

$$(.0001) \quad (.0365) \quad (.0569) \quad (.0034) \quad (.1411)$$

$$R^2 = 93.97\% \quad S/N = 1.12 \quad \gamma = 52.75\%$$

The multiple linear regression model is based on physiological reasoning and field conditions during planting and harvesting. The observed week of planting (PWK) term is included to account for delays in planting; this term is quite significant in the model, despite the fact that it explains only 0.2 percent of the total variation in yields. P_3Q is less significant but explains 1.12 percent of total variance. The interaction between silking time precipitation (P_5) and the number of days exceeding 90°F during the same period (i.e., the product) is very significant in Iowa-East and accounts for 4.6 percent of the total variance. Precipitation around harvest time delays harvesting operations and yields are lower. This may be due to dropped corn or abandoned corn

(Hanway, 1977). The R_{45} precipitation variable accounts for such losses. The model has an R^2 of nearly 94 percent and also has a high signal to noise ratio. The weather variables explain 52.75 percent of the variance remaining after trend removal.

The equation for the Iowa-East stepwise model developed in this study is:

$$\hat{y} = b_o + b_1NIT + b_2PCTNP + b_3P_3Q + b_4P_4 + b_5P_5T90 + b_6R_{45} \quad (46)$$

$$= .62.3 + .54NIT - .14PCTNP + 2.77P_3Q - 5.16P_4 + .44P_5T90 - 2.52R_{45}$$

$$(.8727) \quad (.0000) \quad (.0080) \quad (.0029) \quad (.0640) \quad (.0150)$$

$$R^2 = 96.36\% \quad S/N = 2.5 \quad \gamma = 71.41\%$$

The nitrogen fertilizer term explains about 87 percent of the total variation about the mean yield. The percentage of corn not planted by the long-term average planting week (PCTNP) indicates a delay in planting during any particular year. Precipitation during the early vegetative stage is accounted for by a quadratic form (P_3Q). Precipitation near 75 percent tasseling seems to be detrimental to corn yields. This may be due to excess rain during this period washing pollen from those plants that are already in the pollination stage. This could then reduce corn yields. Again, the interaction between silking time precipitation and temperature stress explains over 6 percent of the total variation. The stepwise procedure also picked the precipitation during harvest time (R_{45}) as an important variable. The overall model has a high R^2 value and the signal to noise ratio is 2.5. The weather variables explain 71.4 percent of the variation remaining after trend removal, indicating that the model is reliably weather sensitive.

The Iowa-West model results are shown in Figures 16 and 17. The multiple regression and stepwise models are very consistent with one another. Yield reductions due to delayed planting in 1951 show up significantly in the large residuals. Scattered late spring frosts and heavy rains during harvest time reduced the yield considerably. Both the models are not sensitive to these two weather influences.

The Iowa-East model results are shown in Figures 18 and 19. Both the models perform very well during all years and are also very consistent with one another. According to the 1968 Weekly Weather and Crop Bulletin (USDC and USDA, 1968), the southern and eastern regions of Iowa escaped the late spring freezes during the 1968 growing season.

B.3. Illinois State Corn Models

The equation for the Illinois state multiple linear regression model developed in this study is:

$$
\begin{aligned}
\hat{y} &= b_o + b_1\mathrm{NIT} + b_2\mathrm{PWK} + b_3P_3Q + b_4\mathrm{SM3} + b_5\mathrm{T90}_{12} \qquad (47)\\
&= 100.87 + .43\mathrm{NIT} - 2.70\mathrm{PWK} + 2.14P_3Q + .41\mathrm{SM3} - .30\mathrm{T90}_{12}\\
&\qquad\quad (.9171) \quad (.0020) \quad (.0053) \quad (.0211) \quad (.0080)\\
&\qquad\quad (.0001) \quad (.0584) \quad (.0368) \quad (.1686) \quad (.0947)
\end{aligned}
$$

$$R^2 = 95.35\% \quad S/N = .78 \quad \gamma = 43.90\%$$

The nitrogen trend explains 91.71 percent of the total variation in the mean yield, leaving only 3.64 percent of the unexplained variance to the weather variables. Soil moisture during the silking and pollination stages (SM3) accounts for 2.1 percent of the total variance, despite the fact that it is the least significant variable. Planting date studies by Zuber (1968) indicate a non-linear relationship between corn yields and date of planting. Therefore, a negative coefficient for PWK does not

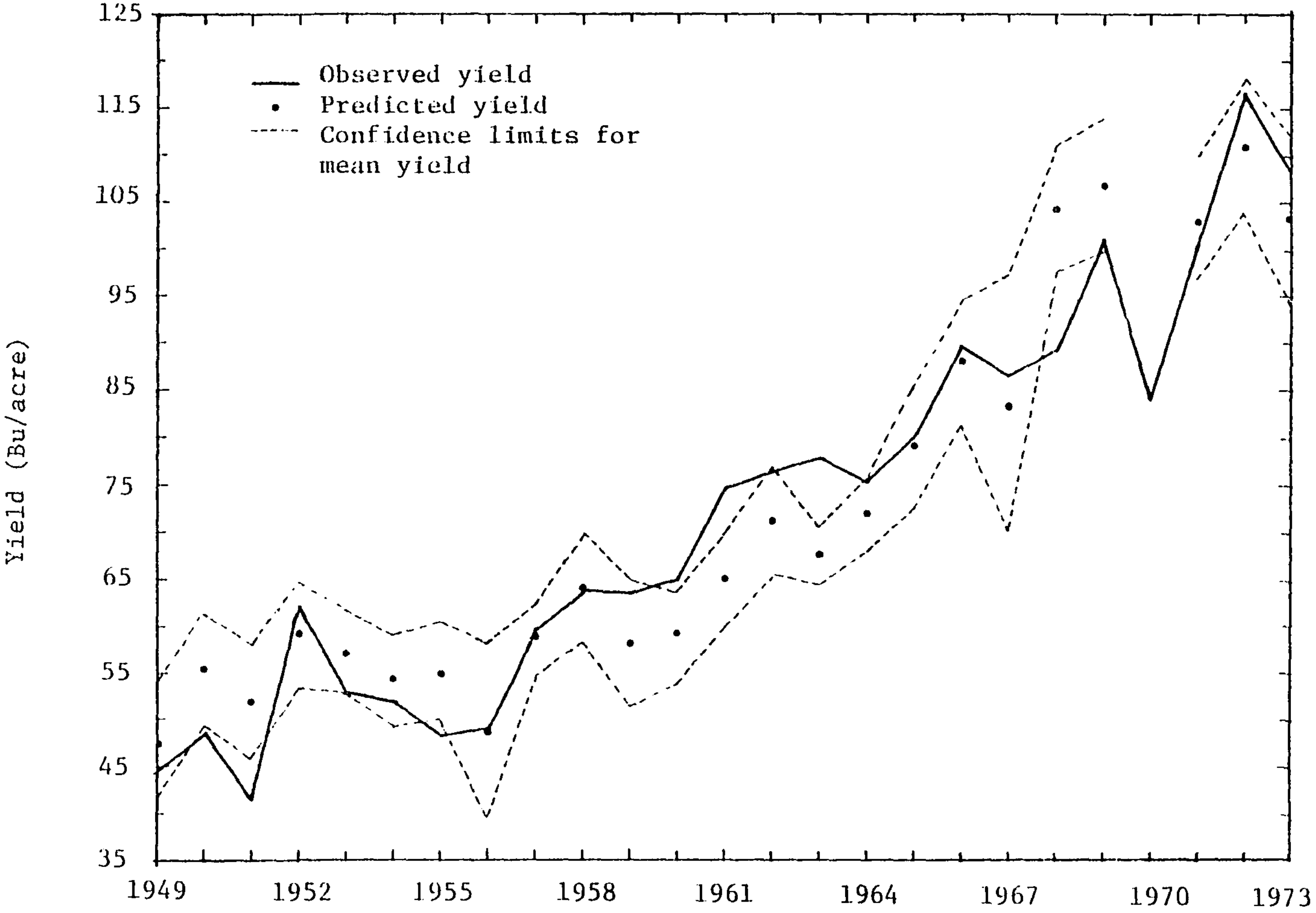

Figure 16. Observed and Predicted Yields for Iowa-West using the Multiple Regression Model. The Blight Year (1970) is excluded from the Analysis.

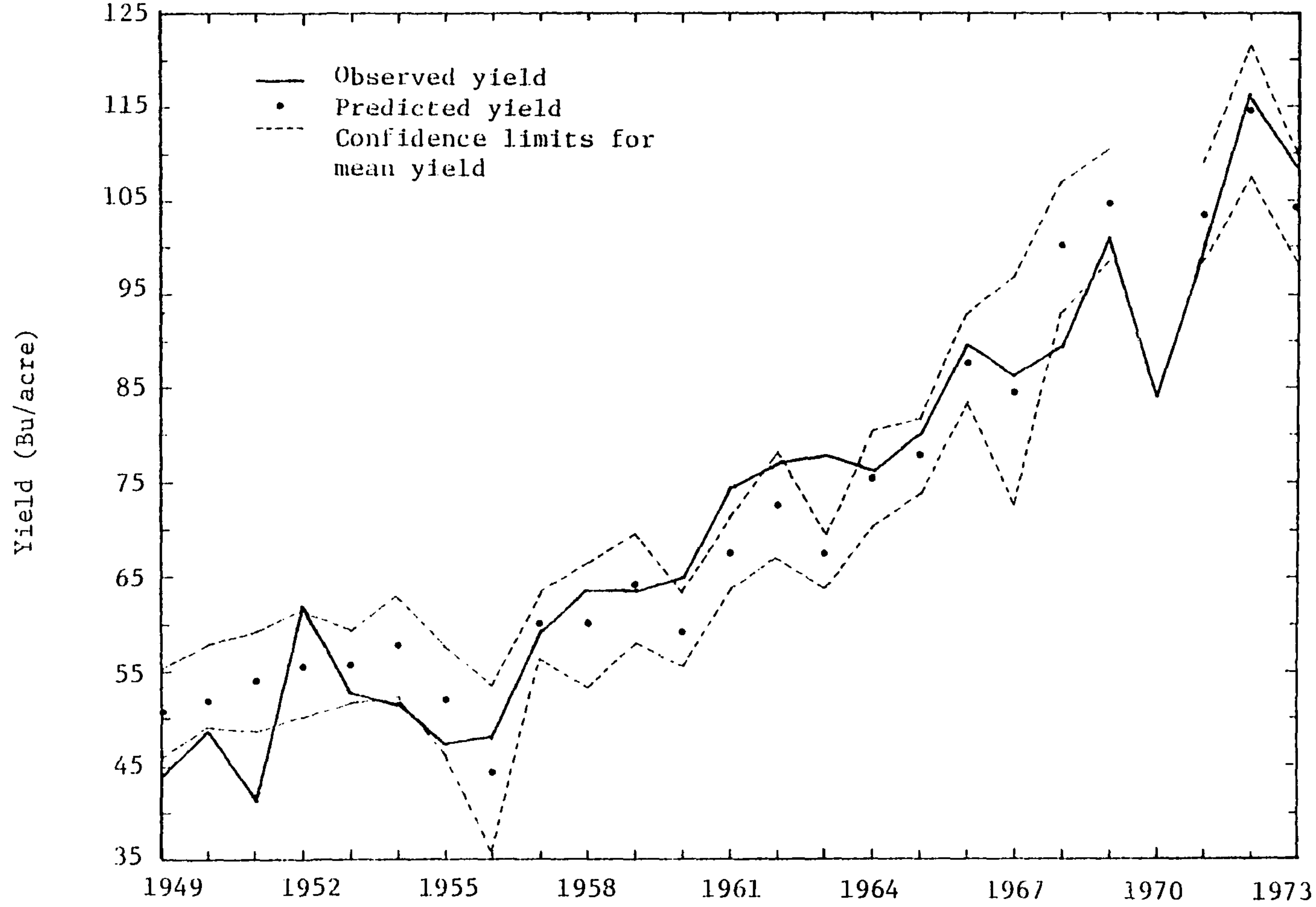

Figure 17. Observed and Predicted Yields for Iowa-West using the Stepwise Procedure Model. The Blight Year (1970) is excluded from the Analysis.

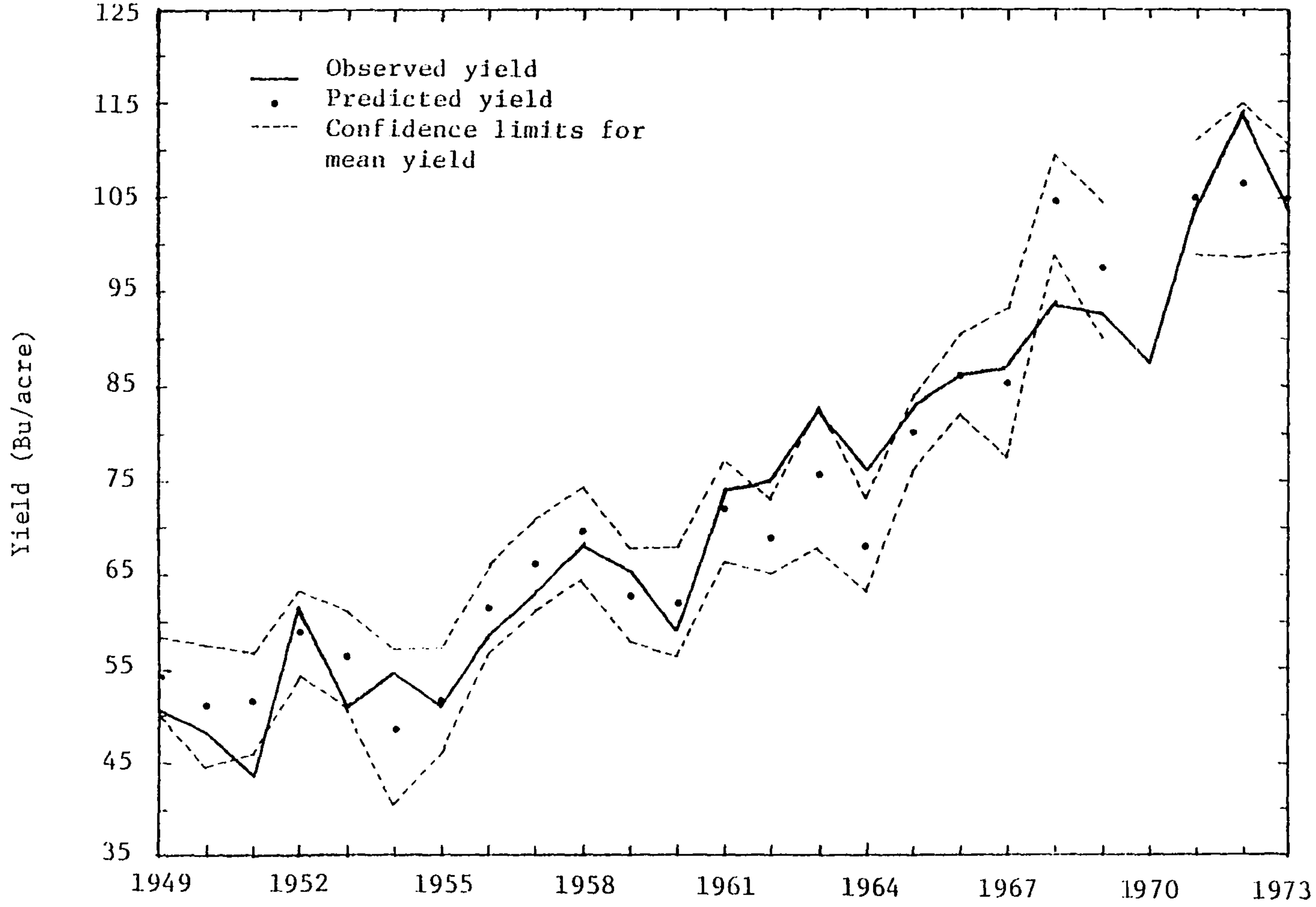

Figure 18. Observed and Predicted Corn Yields for Iowa-East using the Multiple Regression Model. The Blight Year (1970) is Excluded from the Analysis.

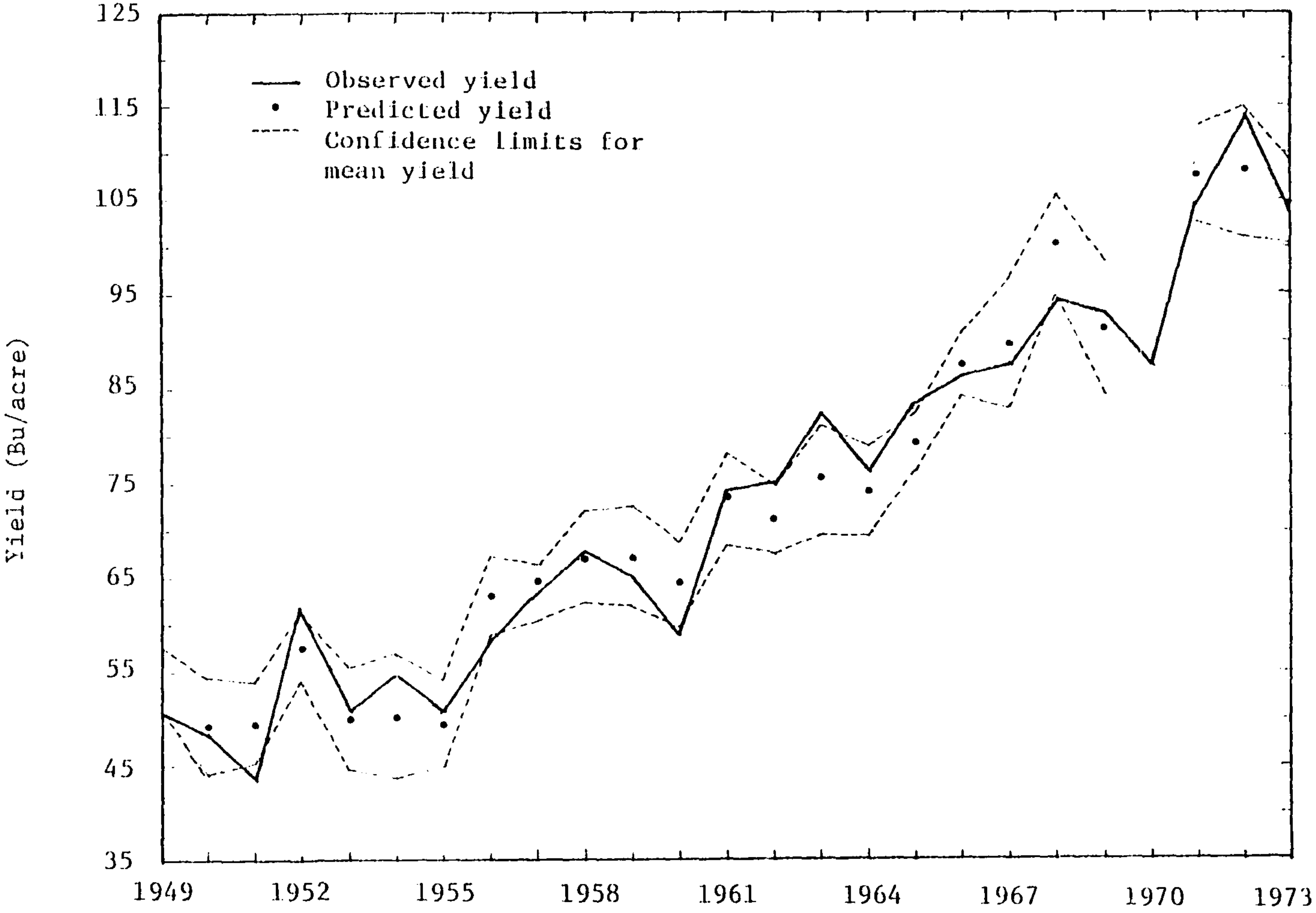

Figure 19. Observed and Predicted Corn Yields for Iowa-East using the Stepwise Procedure Model. The Blight Year (1970) is Excluded from the Analysis.

necessarily imply best yields for corn that is not planted at all (PWK = 0); it means the model is giving more weight to delayed plantings. Substitution of a non-linear term for PWK should clear this ambiguity. It is generally accepted that temperature stress (days above 90°F) during the silking and pollination stages ($T90_1$) reduces yield (Hanway, 1977; Shaw, 1977). During the early developmental stages of this model, it became apparent that temperature stress during two to five weeks after silking ($T90_{20}$) is also important and so the two terms have been combined ($T90_{12}$). This bimodal response to temperature stress may be attributed to a varietal mix of corn. Varietal information on corn planted over the 1949-1973 period is not available at present. Therefore, it is difficult to make any definite conclusions on this issue.

The overall model has an R^2 value of 95.35 percent, the weather variables explain 43.9 percent of the variance remaining after removal of the trend.

The equation for the Illinois state stepwise corn yield model developed in this study is given by:

$$\begin{aligned} \hat{y} &= b_o + b_1 NIT + b_2 PCTP21 + b_3 P_3 Q + b_4 T90_{12} \qquad (48) \\ &= 35.17 + .45NIT + .23PCTP21 + 1.91P_3Q - .39T90_{12} \\ &\qquad\quad (.9171) \quad (.0092) \qquad (.0061) \quad (.0216) \end{aligned}$$

$$R^2 \approx 95.40\% \quad S/N = .81 \quad \gamma = 44.60\%$$

The stepwise procedure does not feature the soil moisture (SM3) and planting date (PWK) terms. In Illinois, soil moisture is generally not a limiting factor, temperatures in excess of 90°F are quite common during the silking and pollination stages. In order to determine if the current planting season is ahead or behind schedule, the percentage of corn planted by week 21 (PCTP21) has been included in the model (variable is significant at $\alpha = .05$ level). The model tells us that higher yields are associated with higher percentages of corn planted by week 21. The quadratic term P_3Q features also in the stepwise procedure. Model statistics for the stepwise model are quite similar to the multiple regression model. In fact the latter model is slightly better.

Model results from the multiple regression and stepwise procedures for Illinois state are shown in Figures 20 and 21, respectively. Both the models are very consistent with one another. The two models underestimate yield during the favorable 1960's, it should be pointed out that these deviations are well within one standard deviation of the sample yield.

B.4. Illinois Macro-CRD Models

The equation for the Illinois-North multiple linear regression model developed in this study is given by:

$$\begin{aligned}\hat{y} &= b_o + b_1 NIT + b_2 P_1 + b_3 P_5 + b_4 T90_{12} + b_5 H_{48} \qquad (49)\\ &= 44.45 + .39NIT - 1.26P_1 + 2.45P_5 - .19T90_{12} + .09H_{48}\\ &\qquad\quad (.9413) \quad (.0044) \quad (.0175) \quad (.0031) \quad (.0024)\\ &\qquad\quad (.0001) \quad (.1169) \quad (.0043) \quad (.1851) \quad (.2459)\end{aligned}$$

$$R^2 = 97.05\% \quad S/N = .99 \quad \gamma = 49.70\%$$

Nitrogen fertilizer accounts for 94.13 percent of the total variation in the mean yield. Weather variables explain the remaining 2.92 percent. According to Equation (49), a decrease of 10 pounds per acre in the fertilizer usage reduces yield by 3.9 bushels per acre whereas an inch or less precipitation during silking and pollination (P_5) can reduce yield by 2.45 bushels per acre. A further loss of 1.26 bushels

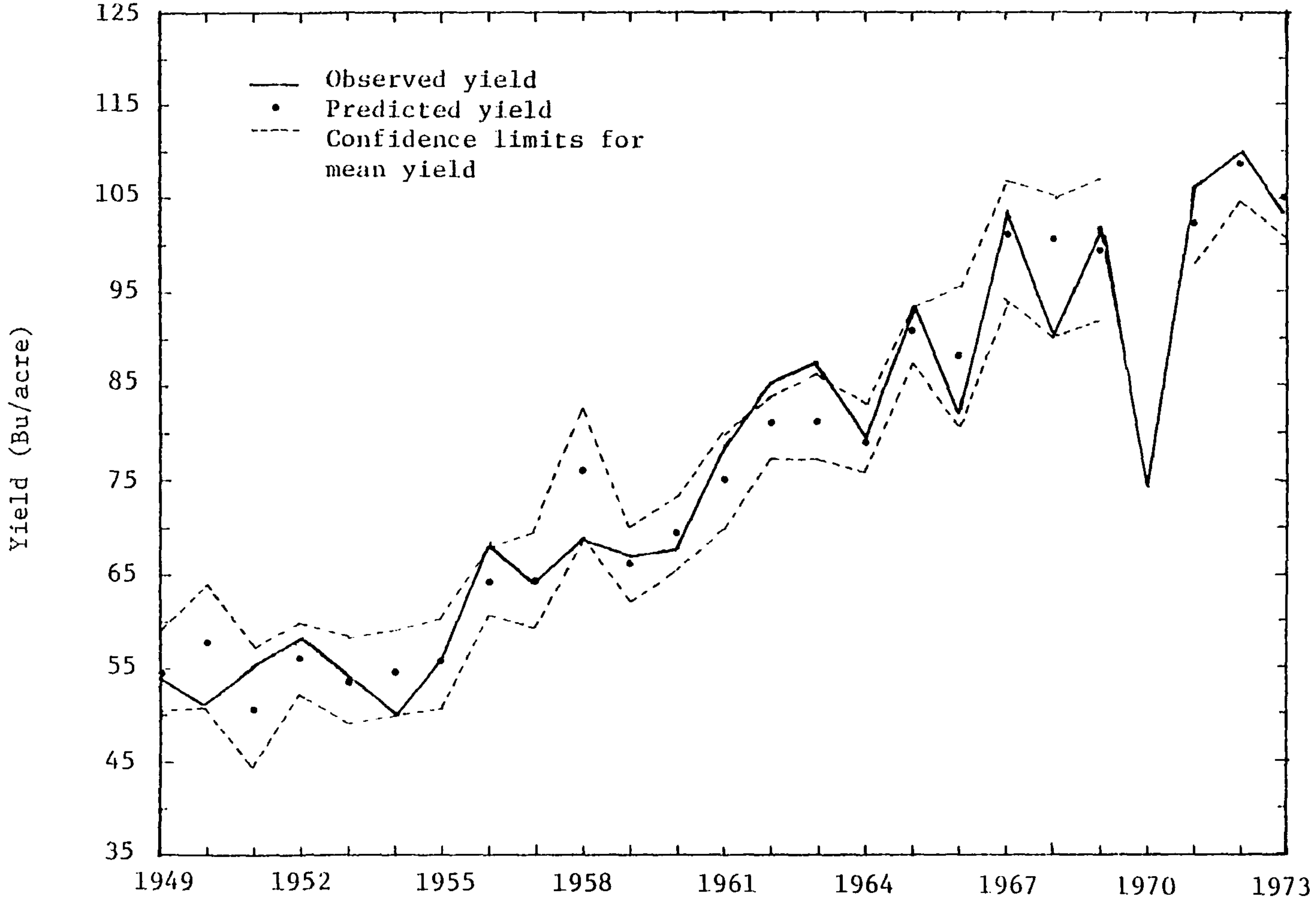

Figure 20. Observed and Predicted Corn Yields for Illinois State using the Multiple Regression Model. The Blight Year (1970) is Excluded from the Analysis.

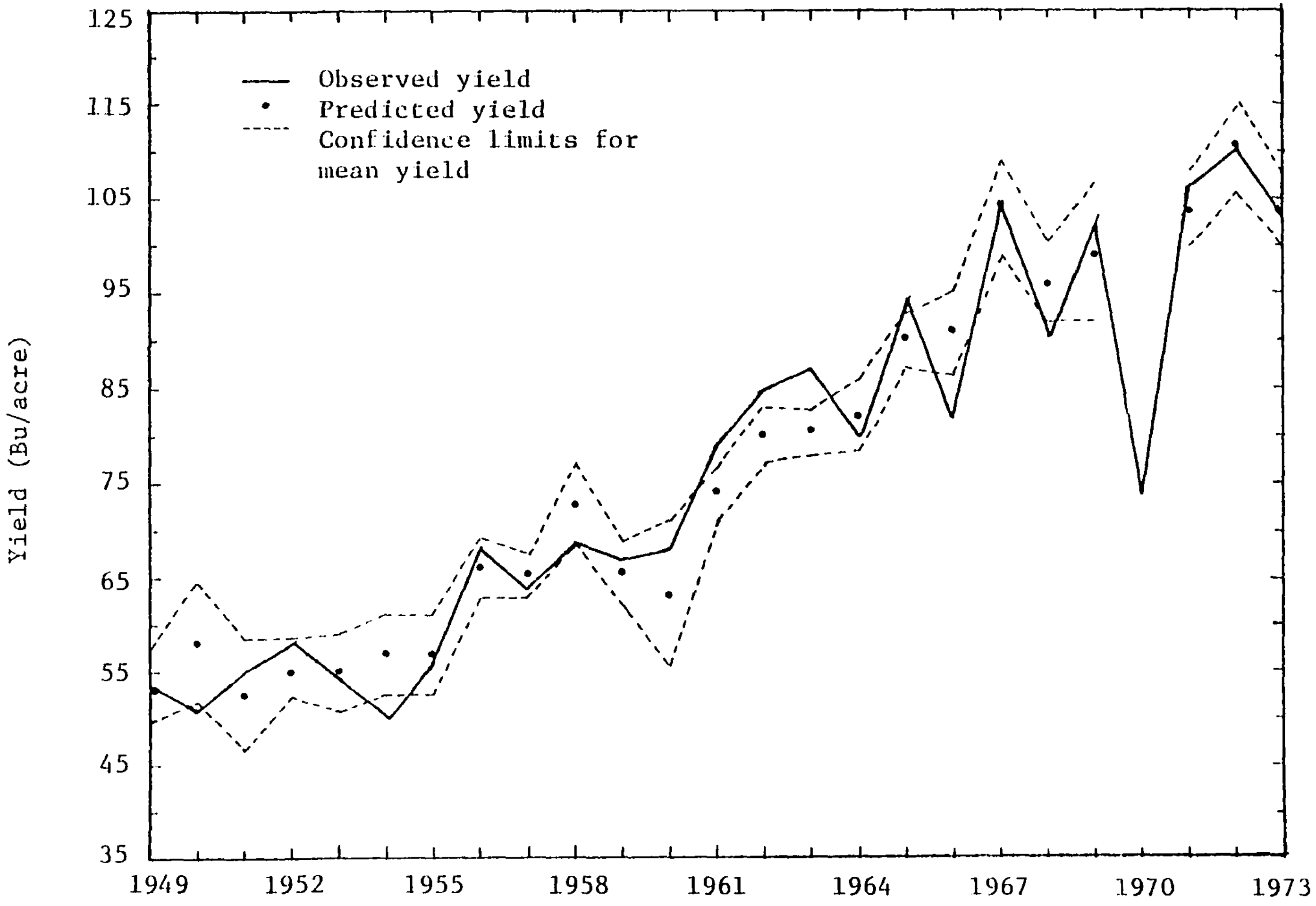

Figure 21. Observed and Predicted Corn Yields for Illinois State using the Stepwise Procedure Model. The Blight Year (1970) is Excluded from the Analysis.

per acre will occur if there is an additional inch of precipitation during planting (P_1). Large fluctuations in yield will then occur when either fertilizer usage is high and weather is favorable, or, when a decrease in fertilizer usage is accompanied by unfavorable weather; random events such as disease epidemics, insect damage and floods are also capable of inflicting severe losses in yield.

Heavy rains during harvest time delay harvesting operations and yield losses due to dropped and abandoned corn are common. The percentage of corn harvested by week 49 (H_{43}) has therefore been included as a variable in the model. The model has an R^2 value of 97.05 percent and the weather variables account for 49.70 percent of the variance remaining after the removal of trend.

The equation for the Illinois-North stepwise model developed in this study is given by:

$$\begin{aligned} \hat{y} &= b_o + b_1 NIT + b_2 PCTNP + b_3 P_1 + b_4 P_5 T90 \qquad (50) \\ &= 61.61 + .39NIT - .12PCTNP - 1.53P_1 + .33P_5T90 \\ &\qquad\quad (.9431) \quad (.0169) \quad (.0019) \quad (.0013) \\ R^2 &= 97.45\% \quad S/N = 1.24 \quad \gamma = 55.34\% \end{aligned}$$

The signal to noise ratio is 1.24 indicating less residual noise for this model. The weather variables explain 55.34 percent of variation remaining after the trend has been removed. The stepwise model is statistically better than the multiple regression model. (Note that the R^2 values for both the models are very close.)

Results from the two models are shown in Figures 22 and 23, respectively. The predicted yields reflect very well the change in technology over the years. The confidence limits for the mean yield are

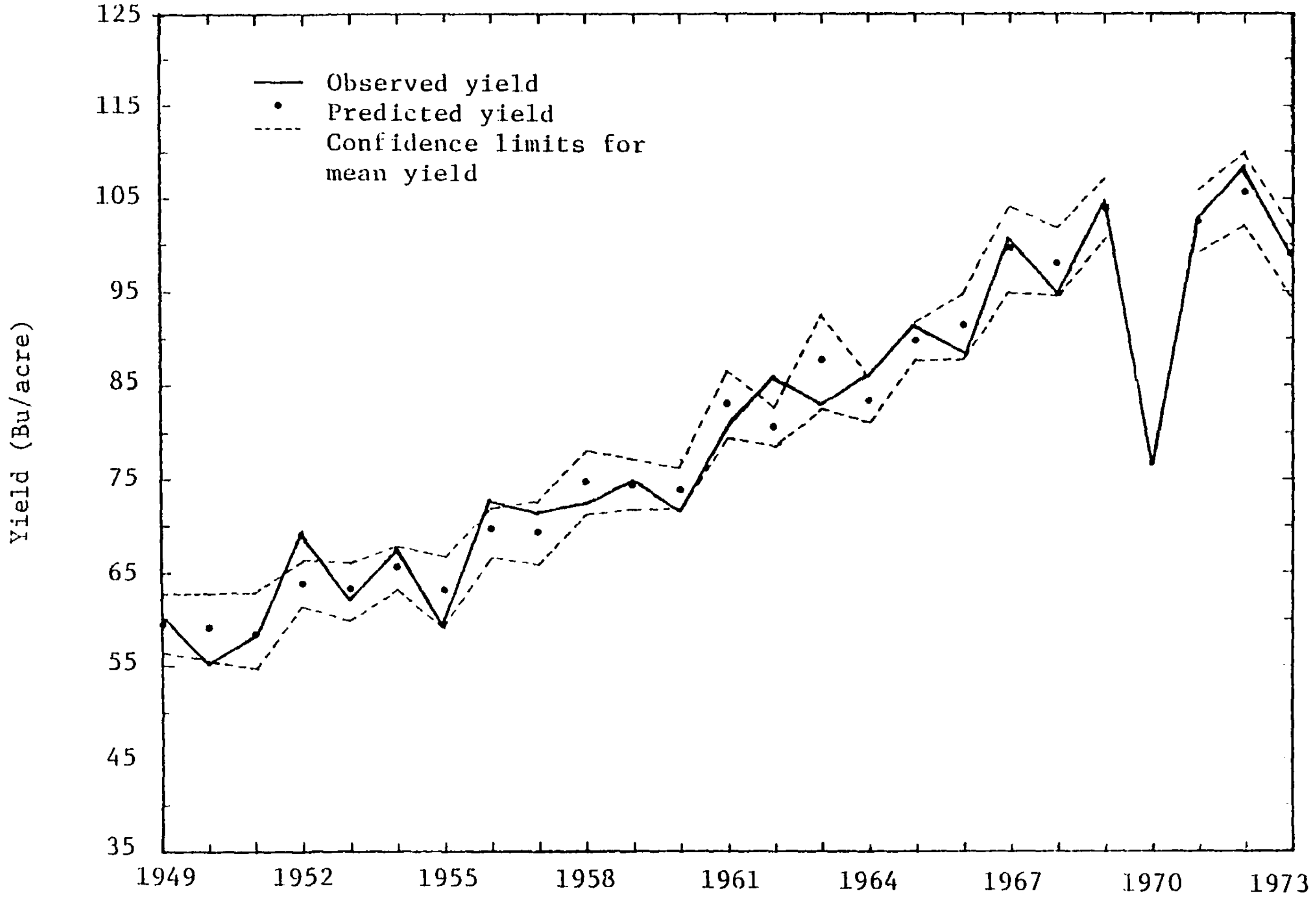

Figure 22. Observed and Predicted Corn Yields for Illinois-North using the Multiple Regression Model. The Blight Year (1970) is Excluded from the Analysis.

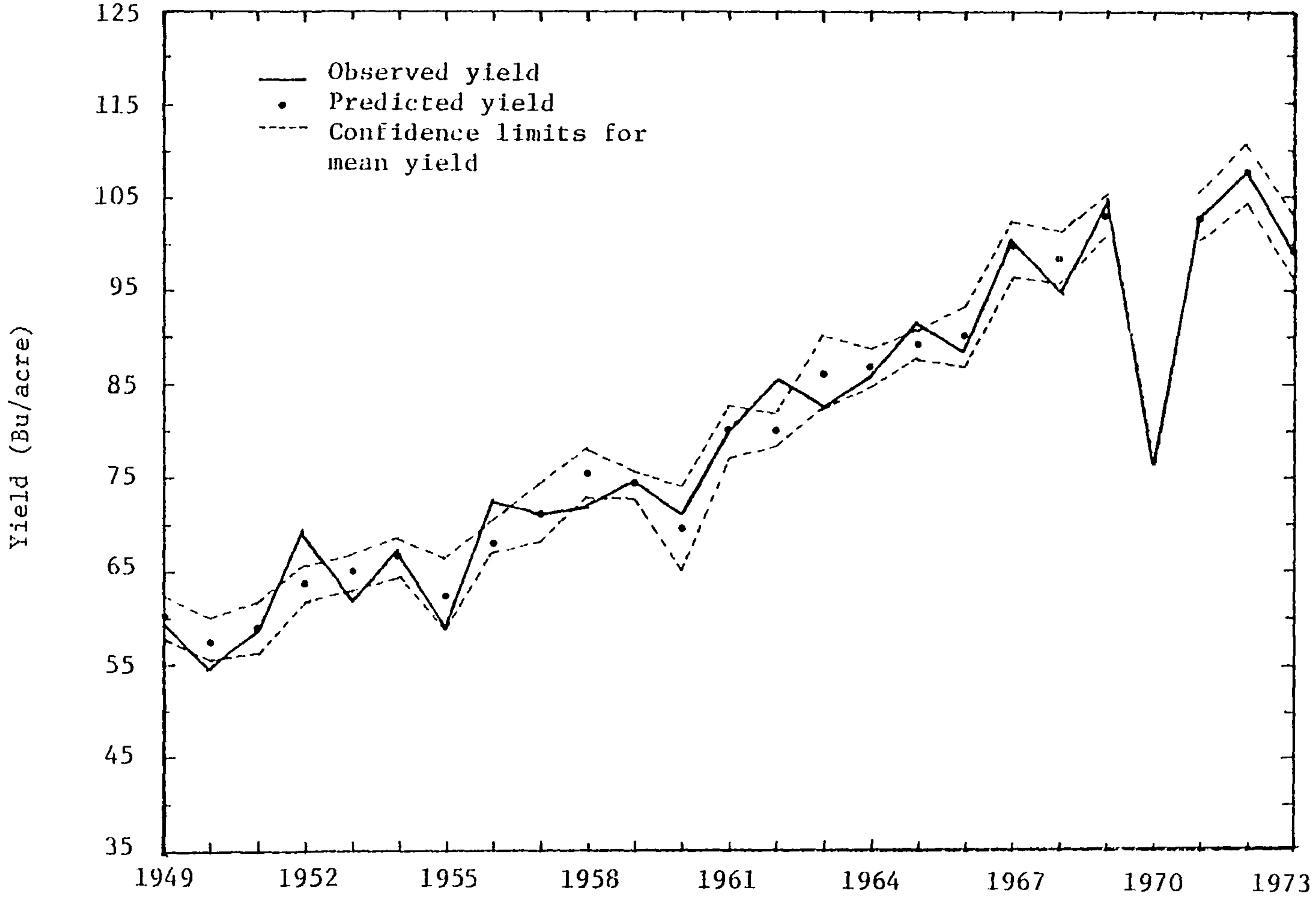

Figure 23. Observed and Predicted Corn Yields for Illinois-North using the Stepwise Procedure Model. The Blight Year (1970) is Excluded from the Analysis.

quite small and encompass the observed yields. Both models have performed remarkably well, especially in the early 1970's.

The equation for the Illinois-Central multiple linear regression model as developed in this study is:

$$\hat{y} = b_o + b_1\text{NIT} + b_3\text{PCTNP} + b_4T_1 + b_5\text{SM3} + b_6R_1 \qquad (51)$$

$$= 2.74 + .51\text{NIT} - .13\text{PCTNP} + .48T_1 + .43\text{SM3} + 1.24R_1$$

(.9035) (.0044) (.0018) (.0149) (.0039)

(.0001) (.2924) (.2950) (.0401) (.3020)

$R^2 = 93.85\%$ S/N = .57 $\gamma = 36.23\%$

Nitrogen fertilizer explains only 90.35 percent of the total variance, but the weather variables explain only 36.23 percent of the remaining variance; nearly 6 percent of the total variance is still unexplained. The percentage of corn not planted by week 21 (PCTNP) and planting time temperature (T_1) are two variables included to account for early season weather influences. Harvest time precipitation (R_{45}) does not seem to cause any appreciable yield reductions in this macro-CRD; however, precipitation two to five weeks after silking shows up to be somewhat important to corn yields here. This could be due to a mix in varieties of corn planted over the years. The soil moisture term (SM3) is again very significant.

The equation for the Illinois-Central stepwise model developed in this study is given by:

$$\hat{y} = b_o + b_1\text{NIT} + b_2P_2 + b_3\text{SM3} + b_4R_1 \qquad (52)$$

$$= 29.78 + .50\text{NIT} - 2.64P_2 + .62\text{SM3} + 2.1R_1$$

(.9035) (.0159) (.0136) (.0145)

$R^2 = 94.75\%$ S/N = .84 $\gamma = 45.70\%$

Precipitation during one to two weeks after planting (P_2) may lead to yield losses due to seed rot or flooded fields. Soil moisture during the silking and pollination stages (SM3) is shown to be important. Precipitation during two to five weeks after silking (R_1) is beneficial to corn plants, this is also the time of rapid dry matter accumulation in the corn ears (Hanway, 1971). An R^2 value of 94.76% and a γ value of 45.70 percent make this a better model than the multiple regression model.

The model results for the multiple regression and stepwise procedure models are shown in Figures 24 and 25, respectively. Both the models predict reasonably well, except during the early 1960's when yields are slightly underestimated. During 1971 the favorable weather during the growing season ensured a good harvest, both the models are underestimating the yield during this year. It should be recalled that 1970 was the corn blight year; therefore, farmers might have taken better precautions against insect damage and plant diseases in 1971.

The equation for the Illinois-South multiple linear regression model developed in this study is:

$$\hat{y} = b_o + b_1 NIT + b_2 P_1 + b_3 P_3 Q + b_4 SM3 + b_5 T90_1 + b_6 R_{45} \qquad (53)$$

$$= 29.77 + 3.7NIT - .81P_1 + 2.45P_3Q + .81SM3 - .70T90_1 - 1.02R_{45}$$

$$\begin{array}{cccccc} (.7847) & (.0000) & (.0143) & (.0638) & (.0241) & (.0073) \\ (.0001) & (.1931) & (.0084) & (.0098) & (.0447) & (.2952) \end{array}$$

$R^2 = 89.43\%$ $S/N = 1.04$ $\gamma = 50.86\%$

Nitrogen fertilizer trend explains 78.47 percent of the total variation in the mean yield, the weather variables explain 50.86 percent of the remaining variance. Also noise level in the model is less than

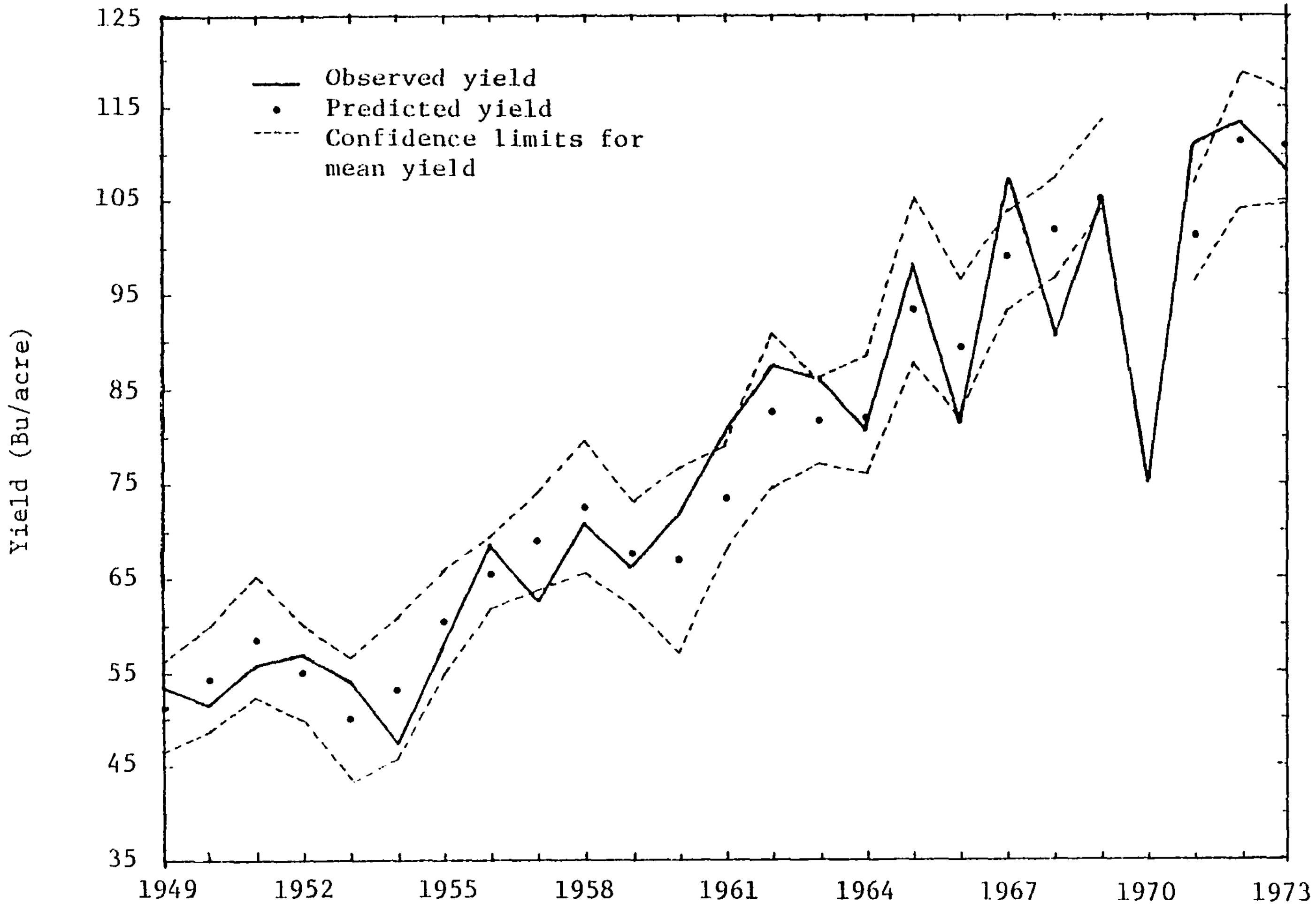

Figure 24. Observed and Predicted Corn Yields for Illinois-Central using the Multiple Regression Model. The Blight Year (1970) is Excluded from the Analysis.

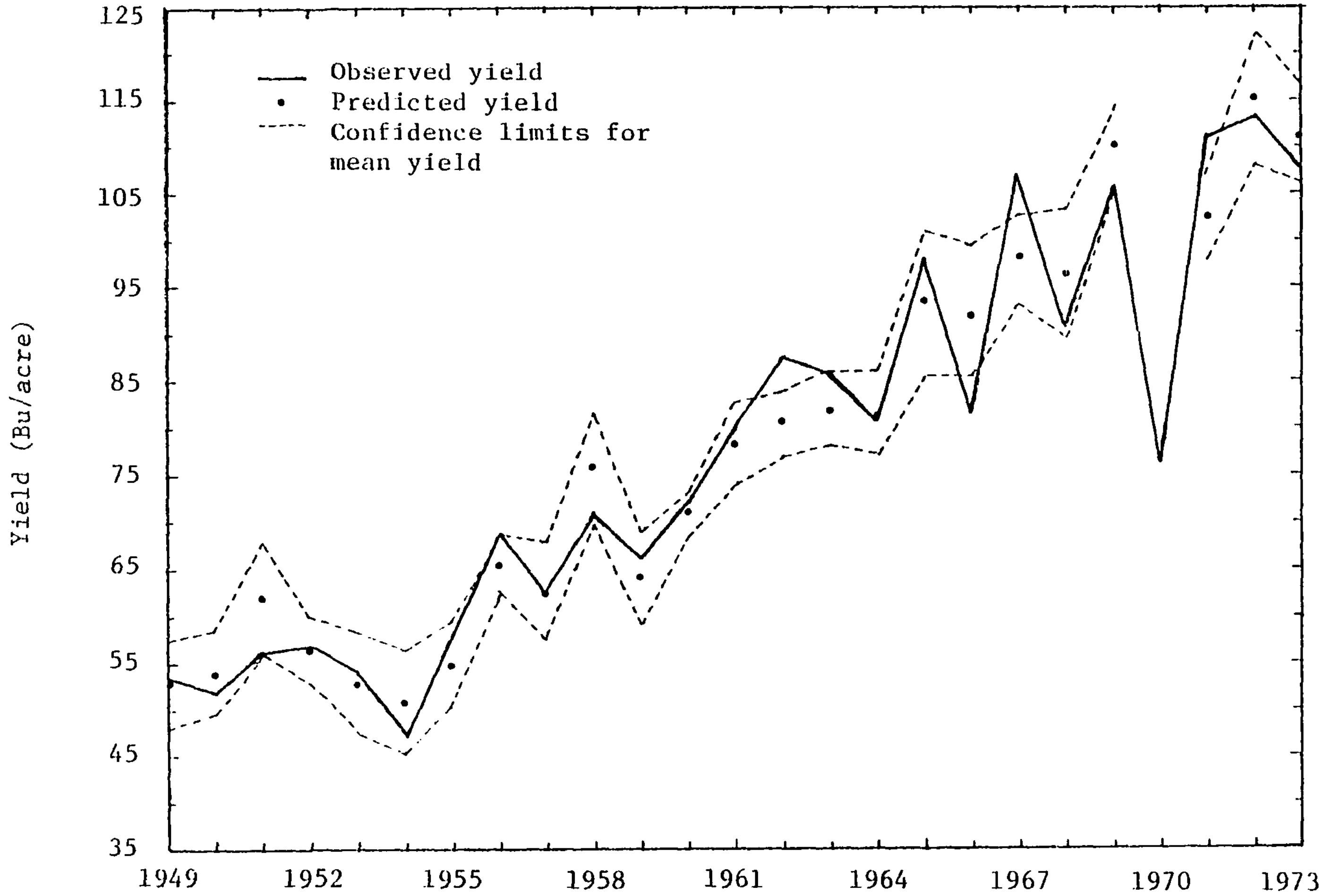

Figure 25. Observed and Predicted Corn Yields for Illinois-Central using the Stepwise Regression Model. The Blight Year (1970) is Excluded from the Analysis.

the signal level. Even though the model has an R^2 value of only 89.43 percent, the estimated yields are very sensitive to the weather variables. All of the weather variables forced into the model are physiologically important to the corn crop. The variables P_1 and P_5 are not very significant, but they should be included in the model in an assessment of its predictive ability.

The equation for the Illinois-South stepwise model as developed in this study is given by:

$$\begin{aligned} \hat{y} &= b_o + b_1 NIT + b_2 T_1 + b_3 T_4 + b_4 S \qquad (54) \\ &= 82.66 + .38NIT + .78T_1 - 1.26T_4 - 2.68S \\ &\qquad\qquad (.7846) \quad (.0186) \quad (.0781) \quad (.0255) \end{aligned}$$

$$R^2 = 90.69\% \quad S/N = 1.31 \quad \gamma = 56.78\%$$

Shaw's moisture stress index (S) is a measure of the accumulated moisture and temperature stress during the growing season and has shown up as significant in the drier southern crop district. Warm temperatures around planting time (T_1) ensure an early planting and quick emergence. High temperatures during the tasseling and silking periods (T_4) lead to delayed silking and poor pollination (Shaw, 1977). The variables T_4 and S are somewhat correlated; however, the coefficients have the proper algebraic sign. The stepwise model has an R^2 value of 90.69 percent and a γ value of 56.78 percent, indicating that this is better than the multiple regression model.

The results from the two models are shown in Figures 26 and 27, respectively. Both the models have a tendency to underestimate yield during favorable years. The dry southern crop district shows the effect of drought during 1954. During 1958, there was an unusually large number

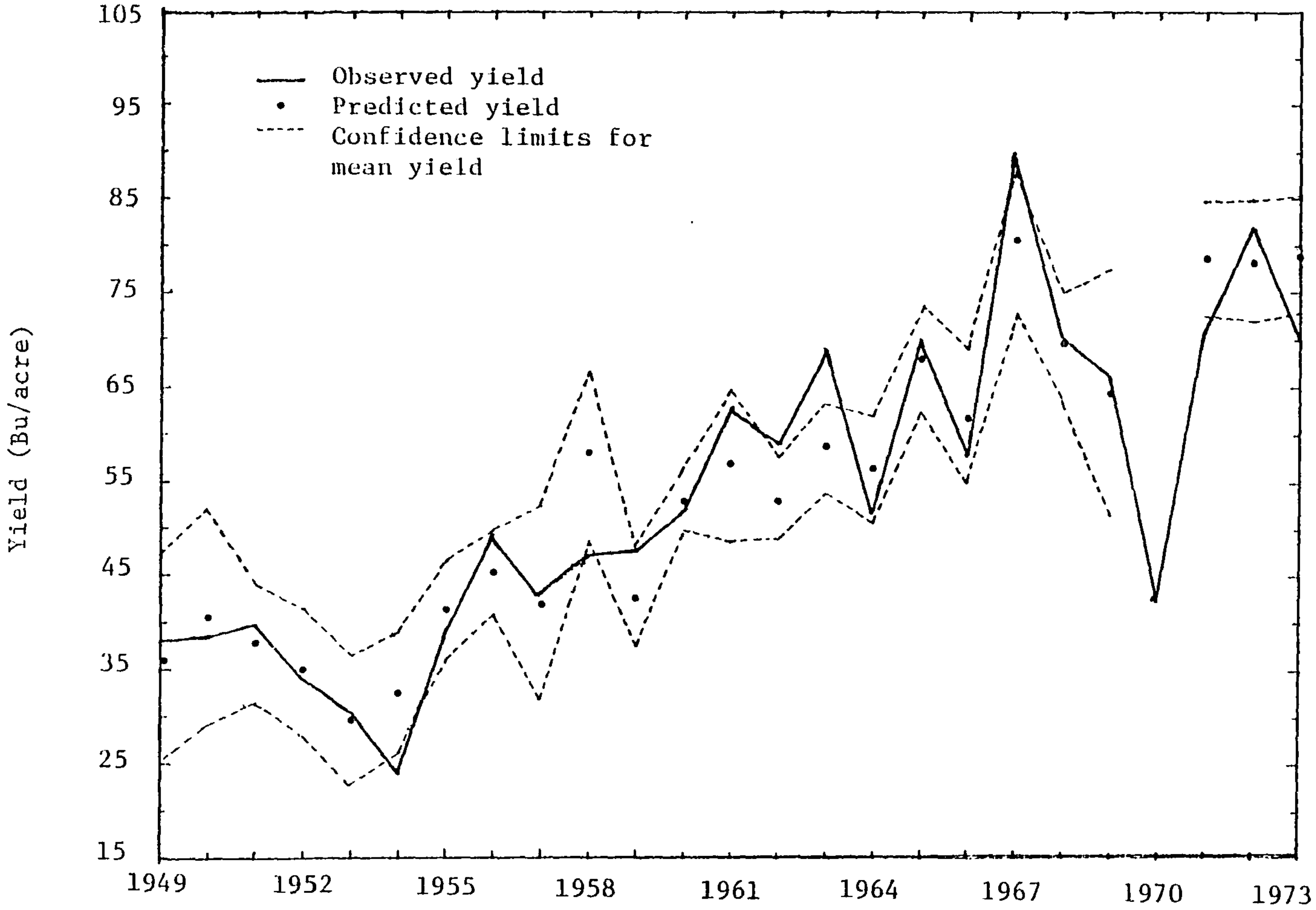

Figure 26. Observed and Predicted Corn Yields for Illinois-South using the Multiple Regression Model. The Blight Year (1970) is Excluded from the Analysis.

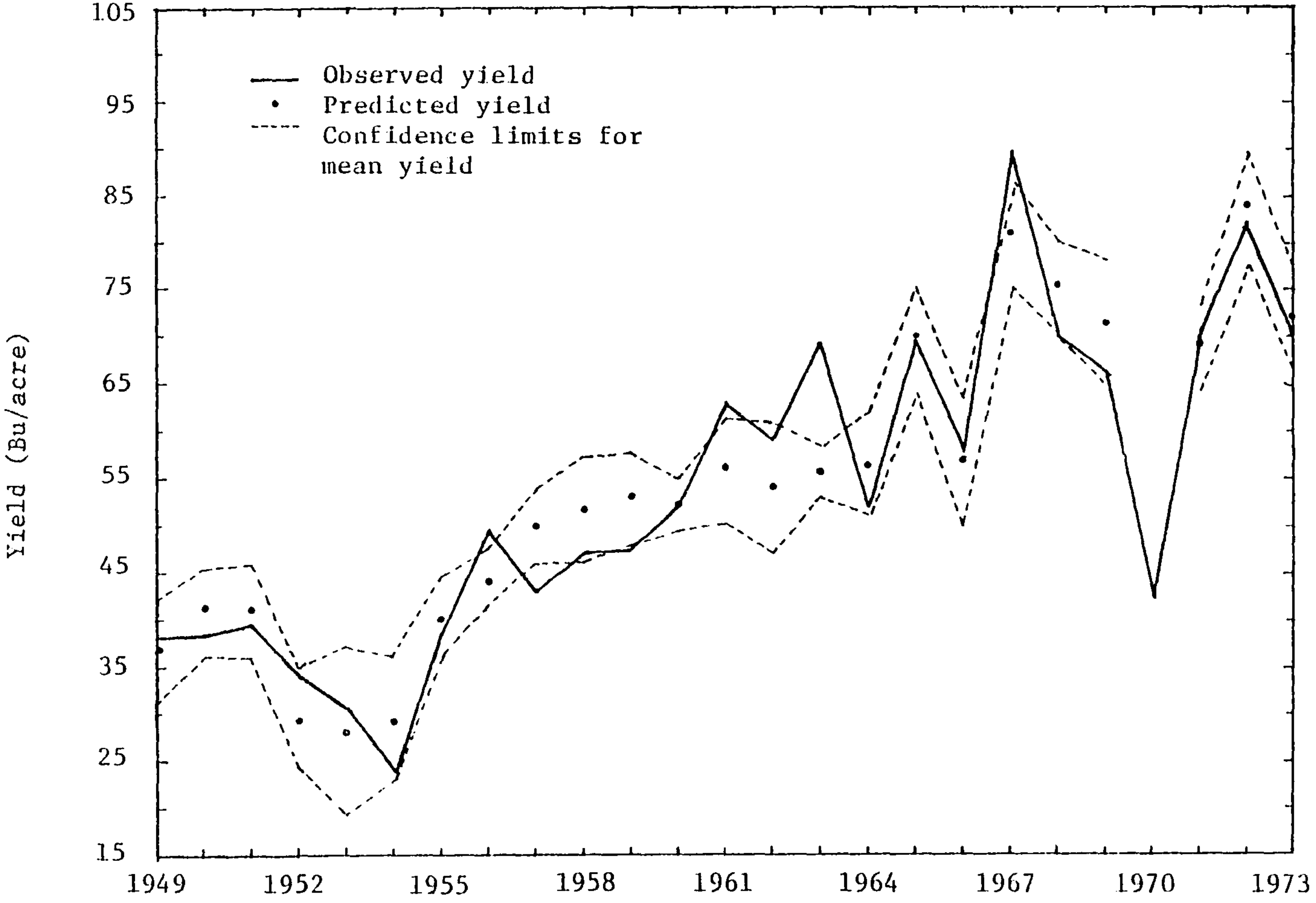

Figure 27. Observed and Predicted Corn Yields for Illinois-South using the Stepwise Procedure Model. The Blight Year (1970) is Excluded from the Analysis.

of days having temperatures in excess of 90°F, the multiple regression model accounted for this stress; however, rains during the silking and pollination period (P_5) gave relief to the crop. The interaction term (P_5T90) is not included in the model and so the yield has been underestimated. The stepwise model uses Shaw's index; this index makes provision for breaks in the dry spell and so yield is not appreciably underestimated. During 1971 and 1975 dry weather prevailed during the grain filling period reducing dry matter accumulation in the corn ears; the multiple regression model cannot account for this as it does not contain the R_1, R_2 and R_3 precipitation variables. However, the stepwise procedure predicts well during 1971 and 1973 because of Shaw's index. The procedure by which this index is computed makes it very difficult for use in operational models, also model truncations cannot be easily made.

C. Model Testing Results

Only one model for each state and macro-CRD has been selected for the testing procedures. The jackknife and bootstrap tests have been performed over the period 1963 to 1973. Independent tests on the individual models are made using the 1974 through 1976 data.

In the jackknife procedure, the data for the year of testing alone is withheld from the analysis whereas in the bootstrap technique, data for the year of testing and beyond is excluded and the model parameters estimated. In both tests, the model parameters so obtained are used to estimate yield during the year of testing.

C.1. Iowa Models

The Iowa-State model testing results are shown in Figure 28. The jackknife test results compare reasonably with the predicted yields using

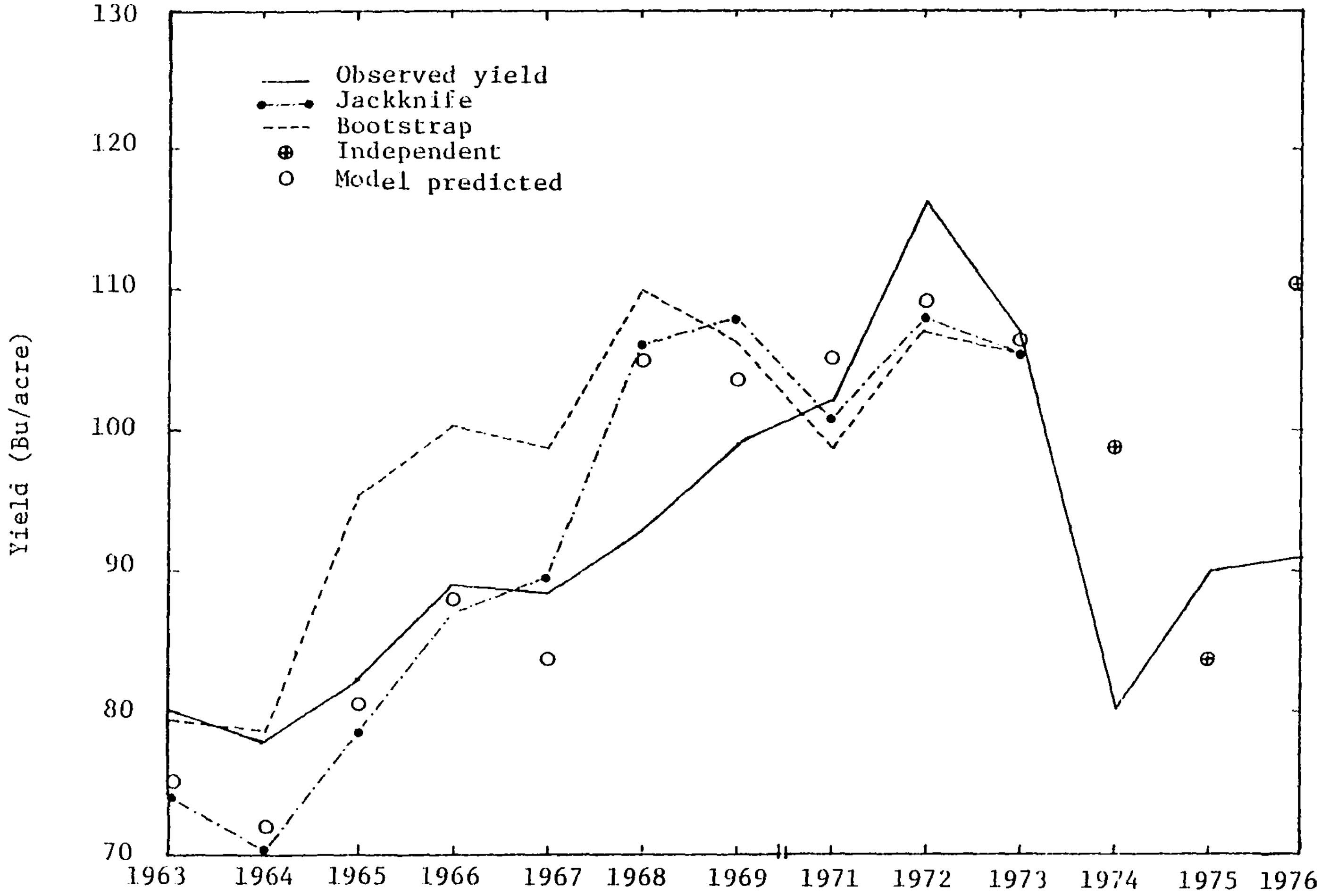

Figure 28. Iowa State Stepwise Model Testing Results.

the 1949-1973 data, indicating that the model coefficients are fairly stable. The bootstrap tests indicate that the model parameters somewhat stabilize after the late 1960's (jackknife and bootstrap test results for the models are tabulated in the Appendix). The observed yields during 1974 to 1976 are very poor compared to the other years. The severe drought of 1974 and the less severe one of 1975, have had their impact on Iowa corn. According to Shaw (1976) western Iowa experienced a more severe drought than the eastern regions during the same period, moisture supplies improved a little during 1975. The average temperatures during the tasseling, silking and pollination stages exceed 80°F during 1975 and 1976, these are well above the 1949-1973 average values (Table 10). Precipitation is seen to be limiting during the early silking through tasseling stages. During 1975 and 1976 the number of days when temperature exceeds 90°F are near normal, but the lack of timely showers added to the problem. The 1974 planting season was delayed by heavy rains, below normal temperatures in the late growing season accompanied by an early fall frost reduced yields considerably (Shaw, 1976).

YR	T_4	T_5	T_6	P_4	P_5	P_6	$T90_{12}$
1974	85.71	87.84	80.10	.57	2.32	3.87	5
1975	88.94	86.68	85.38	.67	1.10	4.43	17
1976	82.98	87.47	84.56	1.21	2.72	1.80	14
1949-1973 Mean	72.90	73.12	70.15	2.40	3.53	3.22	17

Table 10. Some Observed Temperature and Precipitation Values During 1974-1976 in Iowa and Their Corresponding Long-Term Averages

The Iowa-West model results are shown in Figure 29. The jackknife tests show close agreement with the predicted values using the 1949-1973 data, excepting in 1967. The bootstrap tests again show the coefficients to be stabilizing in the early 1970's. The lag in the soil moisture variable reflects in the large residual during 1974, note that the model performs very well during 1975. Very large amounts of nitrogen were applied in 1976, possibly to compensate losses during the earlier years. But the yields are what one might expect with 1965 technology.

Model results from the eastern Iowa models are very encouraging. Both the jackknife and bootstrap tests are very consistent indicating (reference Figure 30) stable coefficients. The model contains numerous weather inputs to account for growing season weather. The severe drought of 1974 and the excessive nitrogen fertilizer usage reported in 1976 are causing the model to overpredict during these two years. The farmers in Iowa have apparently over-fertilized during low soil moisture conditions, following the drought of 1975. Weather, at stages critical to crop growth and development, has to be favorable in order to realize the benefits of massive technological inputs.

C.2. Illinois Models

Results from testing the Illinois state models are shown in Figure 31. The estimated model coefficients from the jackknife and bootstrap tests (refer to tables in the Appendix) have reasonably stabilized since 1969. The model is seen to be overpredicting yield during the years of low yield. The 1974-1976 independent test results also support this statement. The drought of 1974 drastically reduced corn yields; however, 1975 proved to be favorable for the production of corn in Illinois.

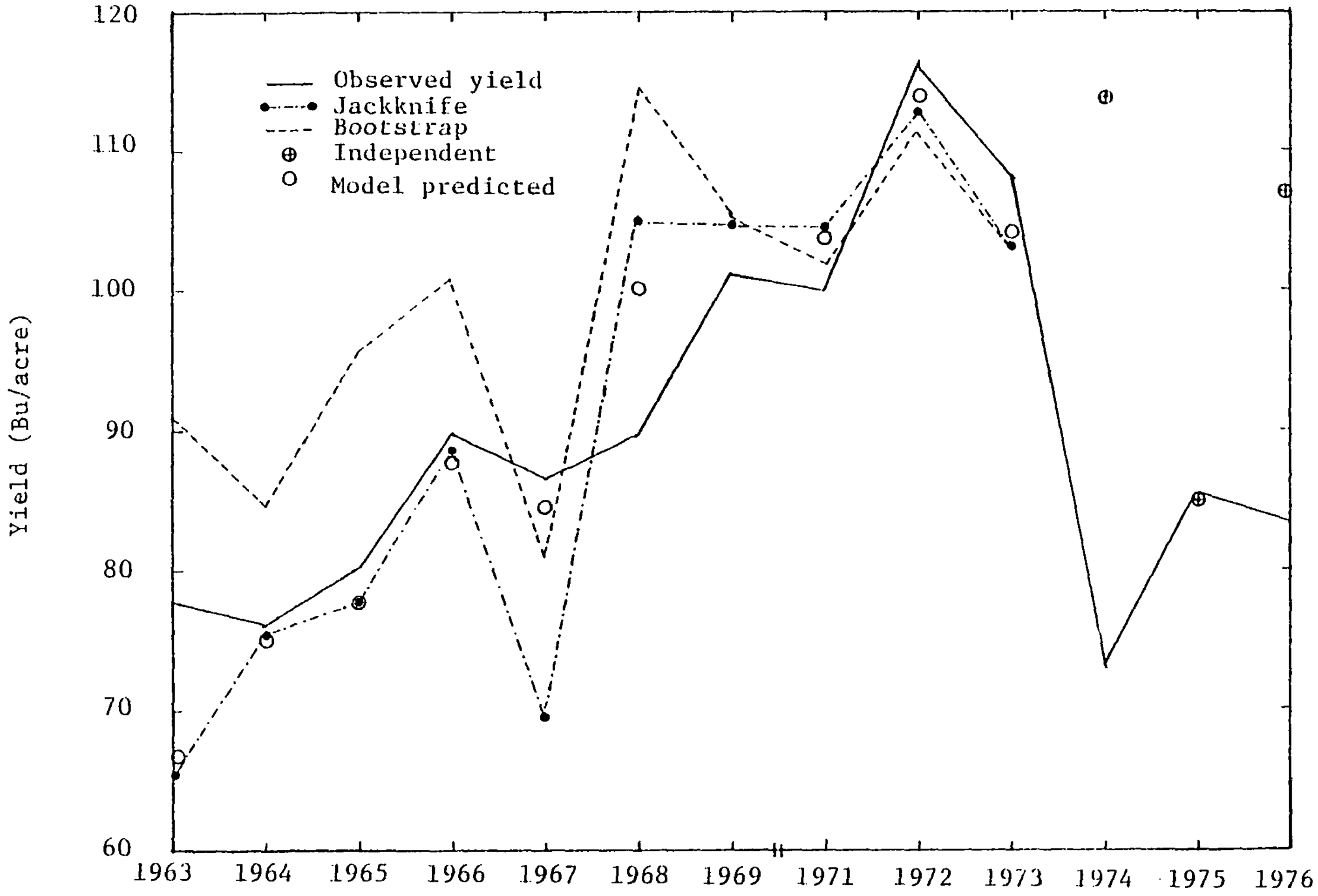

Figure 29. Iowa-West Stepwise Model Testing Results.

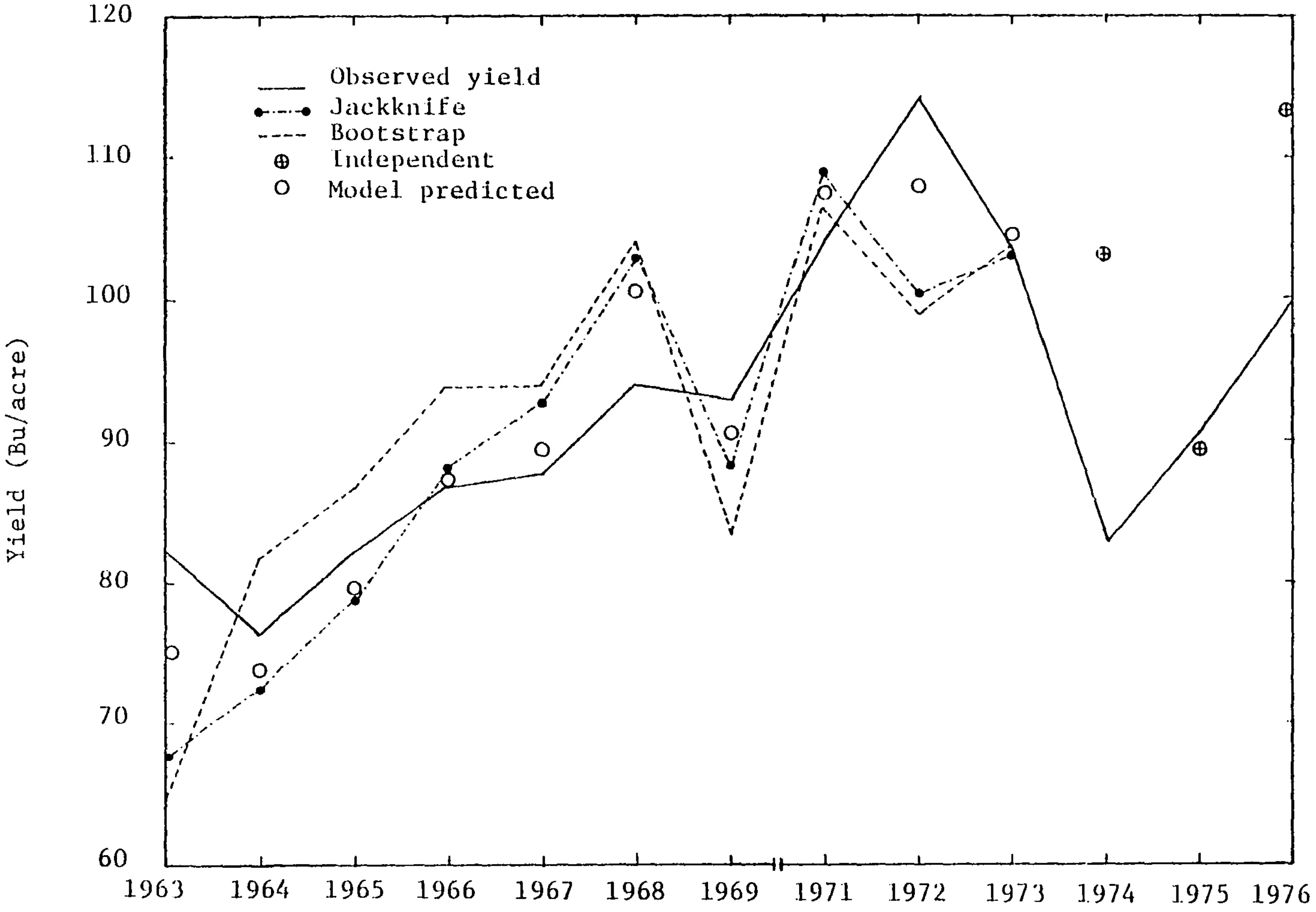

Figure 30. Iowa-East Stepwise Procedure Model Testing Results.

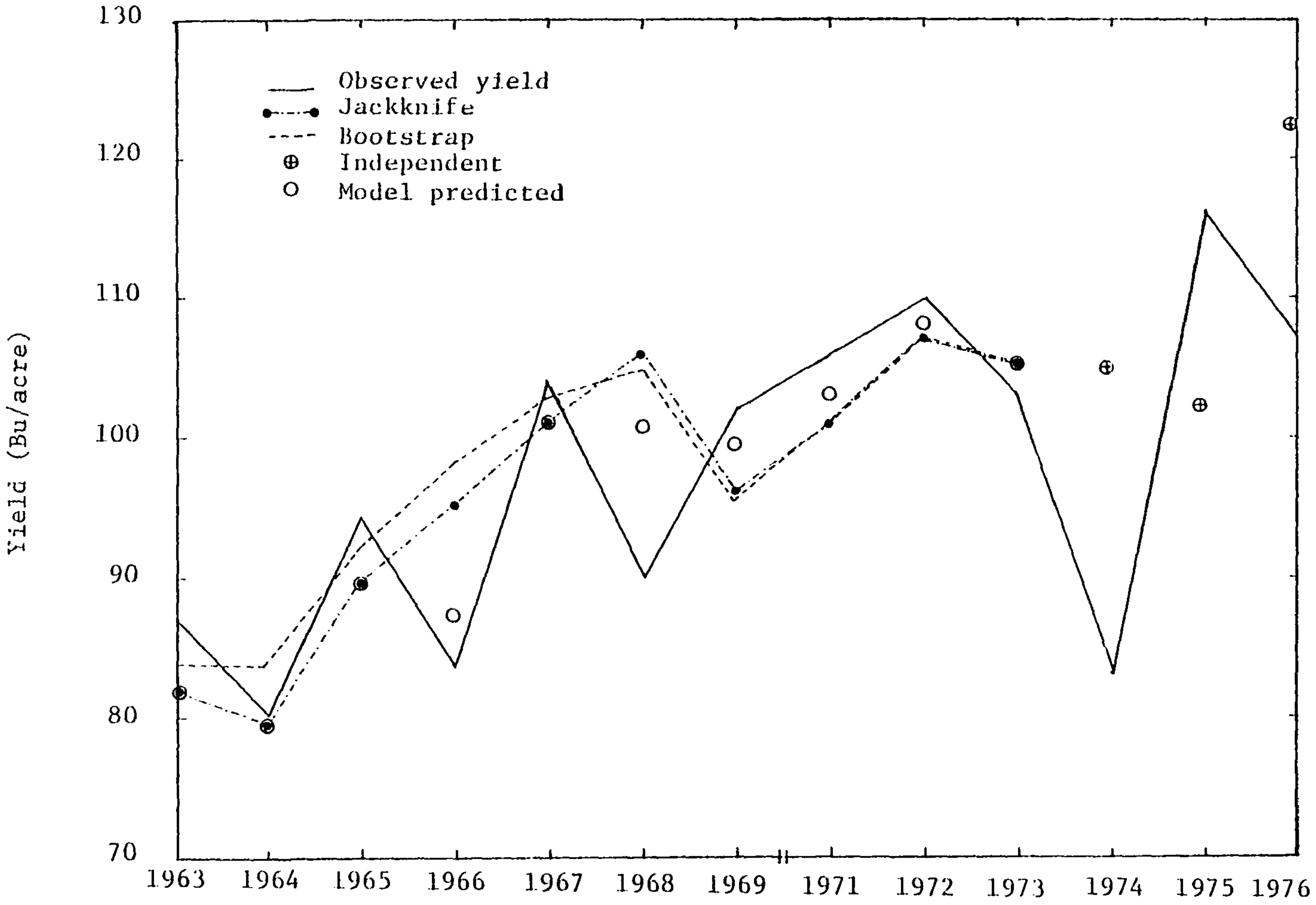

Figure 31. Illinois State Multiple Regression Model Testing Results.

One of the reasons why models fail to perform well during drought years is the trend term itself. Equation (47) tells us that nitrogen explains 91.71 percent of the total variation in the mean yield, leaving out only 3.64 percent of the unexplained variance to the weather variables. Note that this is the basic factor involved while predicting yield for the current year. During a drought year, the trend term does not necessarily explain the percentage of variance empirically required of it; on the other hand, the weather variables easily account for the usual 3 or 4 percent of the total variation in the mean yield. As a consequence, during drought years the weather variables are expected to account for the variation in yield unexplained by the trend. Clearly, the models are not designed to do this and so they fail. Merely including a large number of weather variables in the model, will not resolve the problem as long as the trend term is in the analysis. The trend term does an excellent job when the yields are monotonically increasing as is the case during the 1960's and not otherwise.

Model results for the three Illinois macro-CRDs are shown in Figures 32 to 34. The model coefficients are quite stable, especially for Illinois-North. All the three models overpredicted during the drought year. An interesting feature in Illinois is that the crop response to increased fertilizer usage is generally favorable, especially so during 1976. Fertilizer application rates and available soil moisture reserves are highly correlated, and soil moisture is not generally limiting in Illinois. Farmers in Illinois are therefore likely to expect better return for their fertilizer whenever weather is favorable.

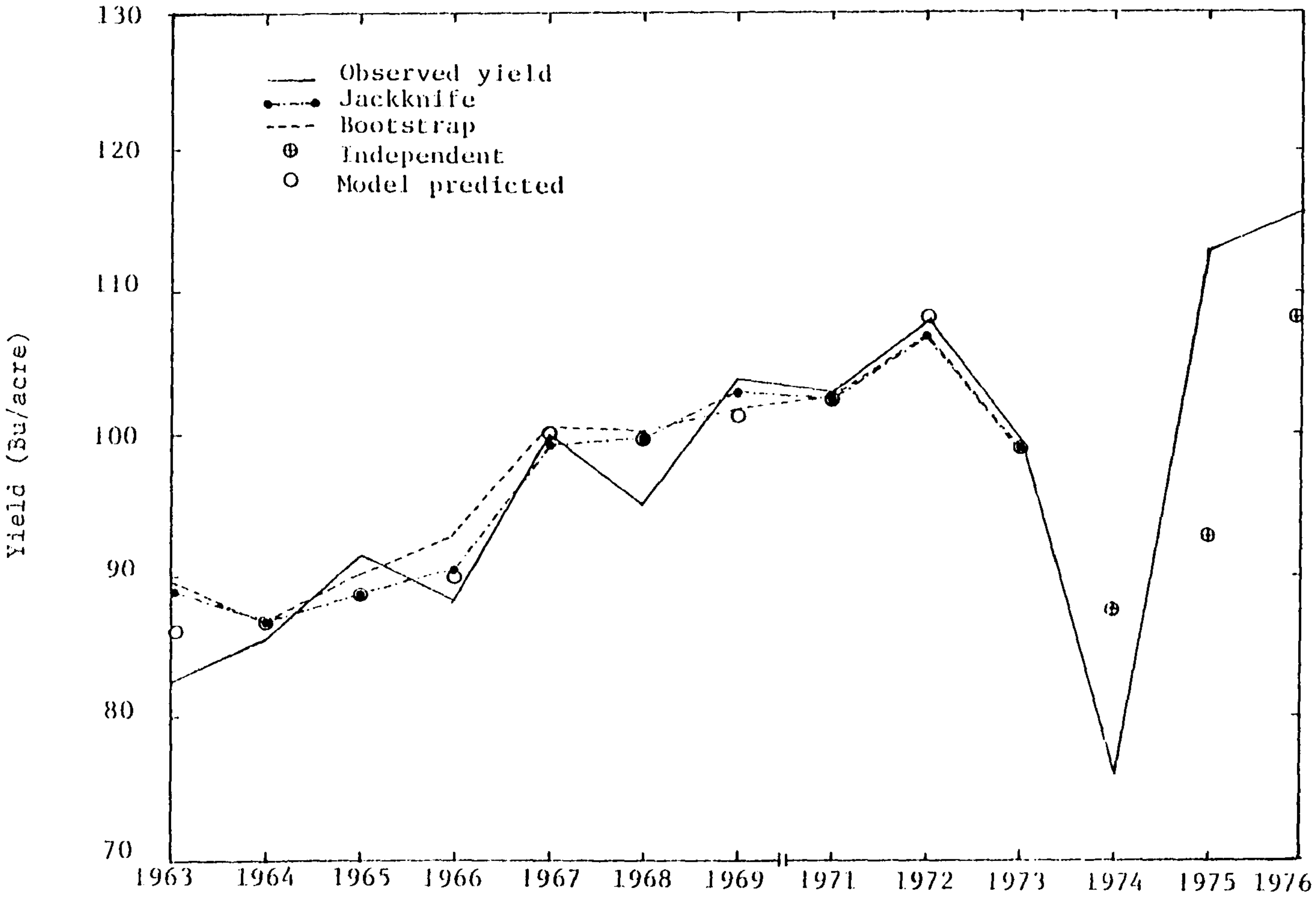

Figure 32. Illinois-North Stepwise Procedure Model Testing Results.

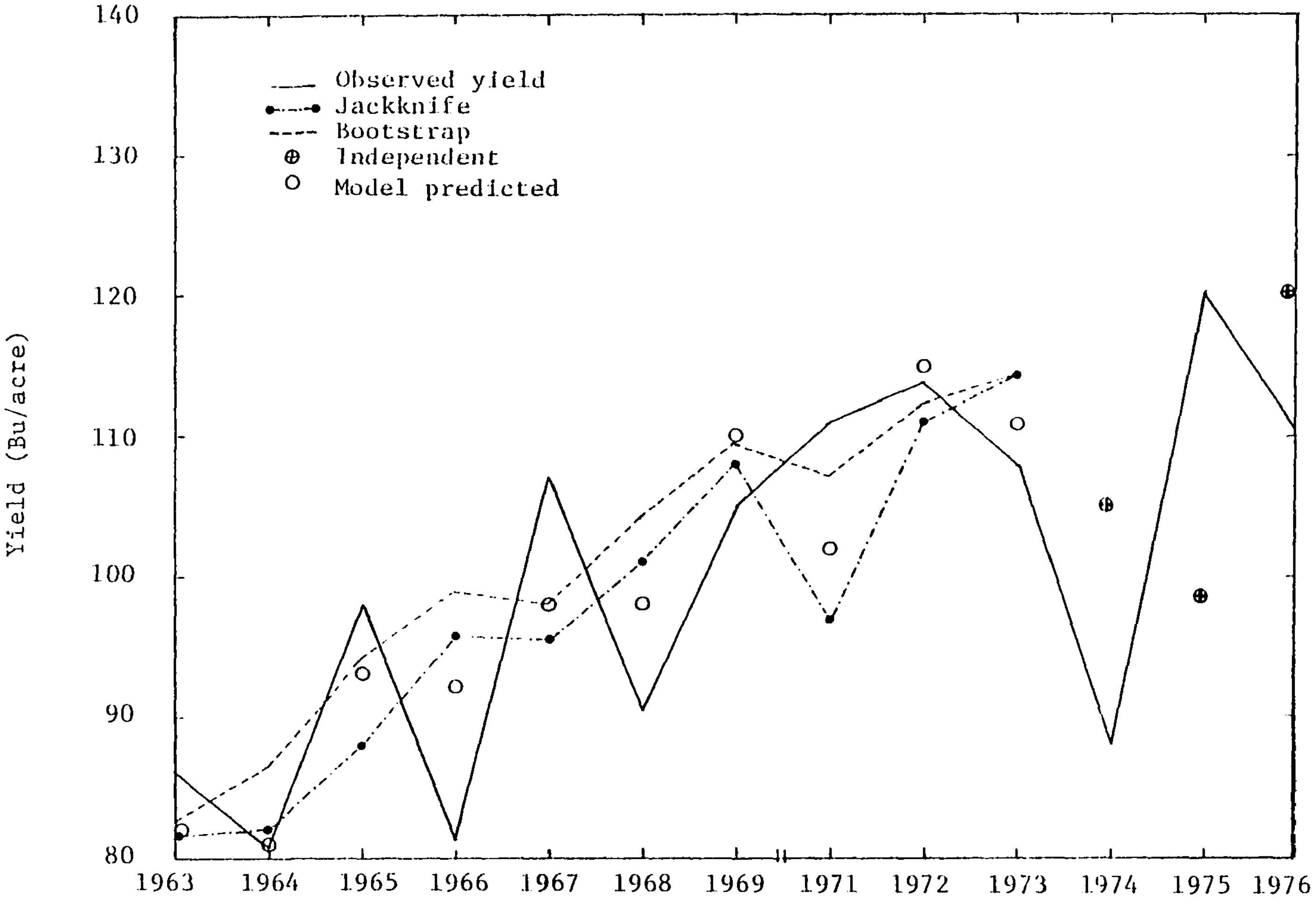

Figure 33. Illinois-Central Stepwise Procedure Model Testing Results.

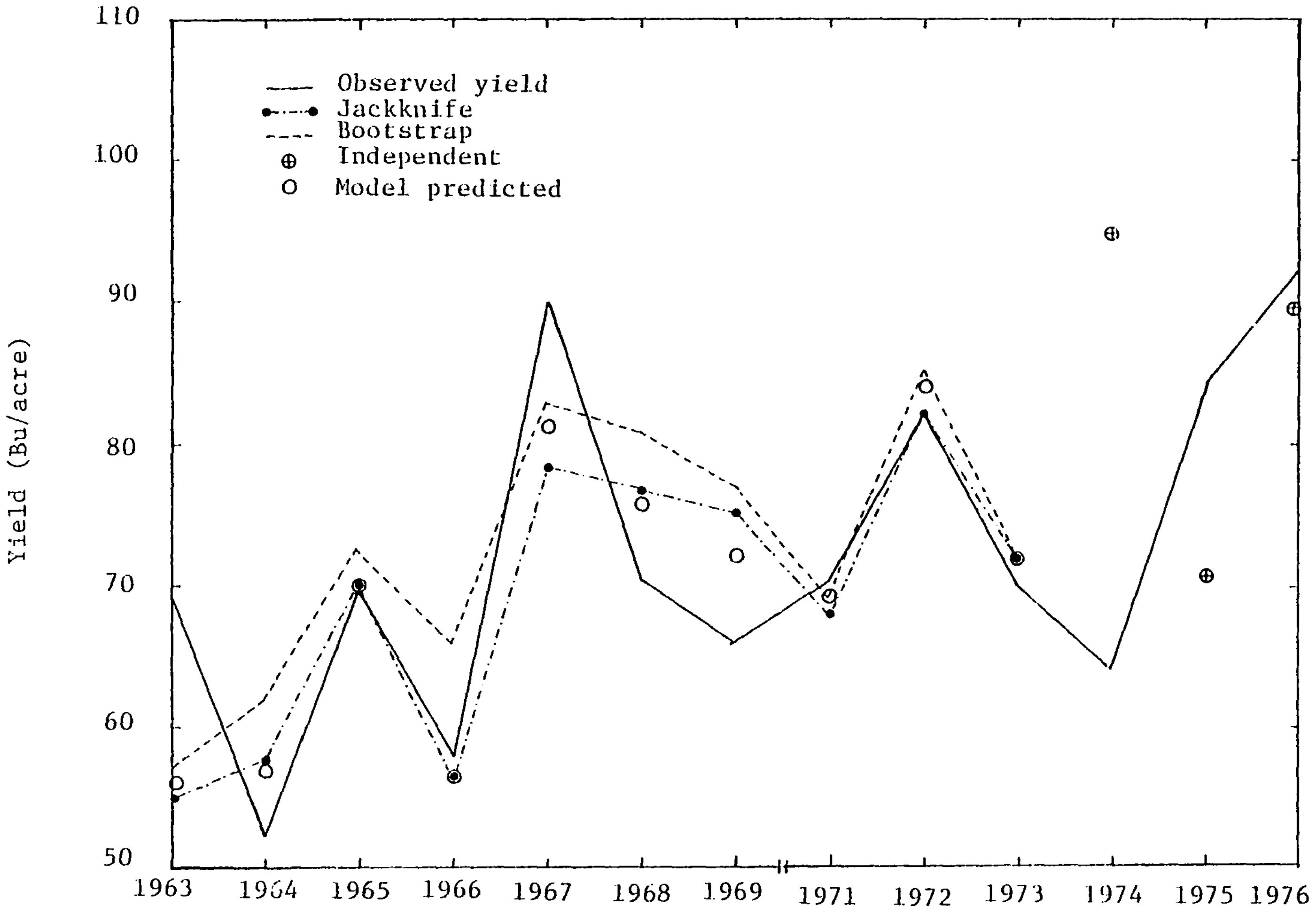

Figure 34. Illinois-South Stepwise Procedure Model Testing Results.

D. Truncated Models

In operational crop yield modeling, it is desirable to predict crop yield at various stages of crop development rather than at the end of the growing season. Truncated models enable the modeler to accomplish this fairly easily. The truncated models, for any given full growing season model, are obtained by recomputing the model parameters using only those variables that fall within the truncation period. In this study the models are truncated once after planting and following silking.

D.1. Iowa-State and Macro-CRD Truncated Models

The truncated models developed for Iowa-state (via Equation (41)) are given in Table 11. Nitrogen is the only model input at the first truncation. The interaction term (P_5T90) during silking improved the R^2 value by an additional 3.28 percent and also resulted in a slight decrease in the standard error (s.e) of Y on X thereby indicating less scatter. The standard error is computed as follows:

$$s.e = \{ \sum_{i=1}^{n} (y_i - \hat{y}_i)^2/(n-2) \}^{1/2} \tag{55}$$

where

y_i = the observed yield during ith year ($i = 1, 2, \ldots, n$) and

$\hat{y}_i$ = the estimated yield during the ith year.

VARIABLE	MODEL TRUNCATION	
	PLANTING	SILKING
β_o	45.13	47.90
NIT	0.56	0.52
P_5T90		0.33
R^2	88.50	91.78
s.e	7.19	6.10

Table 11. Iowa-State Truncated Models (1949-1973)

The truncated models developed for Iowa-West (via Equation (44)) are shown in Table 12.

VARIABLE	MODEL TRUNCATION	
	PLANTING	SILKING
$\hat{\beta}_o$	43.18	22.95
NIT	0.57	0.56
P_3Q		1.51
P_4		-3.22
SM3		0.90
R^2	87.54	93.11
s.e	7.72	5.74

Table 12. Iowa-West Truncated Models (1949-1973)

The addition of three other variables (P_3Q, P_4 and SM3) during the second truncation has increased the R^2 value by 6.36 percent and reduced the s.e by 25.65 percent. Therefore, weather during the planting to silking period is important to corn yield.

The truncated models developed for Iowa-East (via Equation (46)) are shown in Table 13.

VARIABLE	TIME OF TRUNCATION	
	PLANTING	SILKING
$\hat{\beta}_o$	46.44	58.67
NIT	0.52	0.53
PCTNP	-0.004	-0.12
P_3Q		2.59
P_4		-4.45
P_5T90		0.46
R^2	87.27	94.77
s.e (bu/acre)	7.21	4.62

Table 13. Iowa-East Truncated Models (1949-1973)

The table shows that by the time of second truncation the R^2 value has increased by 8.59 percent, and the s.e has decreased by nearly 36 percent indicating a very weather sensitive model.

D.2. Illinois-State and Macro-CRD

Truncated Models

The Illinois-state truncated models have been developed via Equation (47) and are given in Table 14.

VARIABLE	TIME OF TRUNCATION	
	PLANTING	SILKING
$\hat{\beta}_o$	69.38	71.60
NIT	0.46	0.45
PWK	-1.07	-1.97
P_3Q		2.17
SM3		0.68
R^2	91.91	94.55
s.e	5.70	4.70

Table 14. Illinois-State Truncated Models (1949-1973)

Even after including the quadratic term for precipitation during the vegetative stage (P_3Q) and soil moisture during silking (SM3), the model R^2 has improved by only 2.88 percent. This indicates that the model is not very sensitive to weather during the growing season.

The truncated models developed for Illinois-North via Equation (50) are shown in Table 15.

VARIABLE	TIME OF TRUNCATION	
	PLANTING	SILKING
$\hat{\beta}_o$	59.65	61.60
NIT	0.39	0.39
PCTNP	-0.18	-0.12
P_1	-0.60	-1.53
P_5T90		0.33
R^2	96.19	97.46
s.e	3.24	2.63

Table 15. Illinois-North Truncated Models (1949-1973)

The addition of the precipitation-temperature interaction term (P_5T90) has improved the R^2 value by a meagre 1.32 percent. This indicates that in northern Illinois the silking period is quite favorable for the production of corn.

The truncated models for Illinois-Central via Equation (52) are shown in Table 16.

VARIABLE	TIME OF TRUNCATION	
	PLANTING	SILKING
$\hat{\beta}_o$	45.94	36.04
NIT	0.51	0.50
P_2		-2.57
SM3		0.57
R^2	90.35	93.33
s.e	6.73	5.60

Table 16. Illinois-Central Truncated Models (1949-1973)

The silking truncation has improved the R^2 value by 3.30 percent and reduced the s.e by 16.79 percent. This indicates that the model is quite sensitive to the weather inputs P_2 and SM3.

The truncated models developed for the Illinois-South multiple regression model via Equation (53) are given in Table 17.

VARIABLE	TIME OF TRUNCATION	
	PLANTING	SILKING
$\hat{\beta}_o$	30.47	26.79
NIT	0.30	0.38
P_1	0.01	-0.62
P_3Q		2.54
SM3		0.73
$T90_1$		-0.62
R^2	78.47	88.70
s.e	8.05	5.83

Table 17. Illinois-South Truncated Models (1949-1973)

The planting truncation model is not physiologically reasonable because P_1 (precipitation during planting) has a positive coefficient.

However, the model coefficients have stabilized by the time of the second truncation (P_1 has a negative coefficient). This shows that the model parameters may not be very stable during the earlier truncations. Overall, the R^2 value has improved by 13 percent by the time of the second truncation.

Some important statistics for the various Iowa and Illinois crop yield models are summarized in Table 18.

	IOWA			ILLINOIS			
VARIABLE	STATE	WEST	EAST	STATE	NORTH	CENTRAL	SOUTH
σ_Y	20.74	19.78	21.40	19.62	16.16	21.17	16.97
$\sigma_{Y,\ NIT}$	7.19	7.72	7.21	5.78	3.94	6.70	8.10
$\sigma_{Y,\ NLT}$	7.38	8.22	6.56	6.35	5.50	7.06	8.85
$\hat{\sigma}$ (Reg. Model)	6.28	6.85	5.49	4.78	3.14	5.93	6.42
$\hat{\sigma}$ (1st Trunc)	7.36	7.72	7.32	5.85	3.87	6.43	8.24
$\hat{\sigma}$ (2nd Trunc)	6.17	6.70	5.68	5.04	3.24	5.95	6.45
$\hat{\sigma}$ (Step. Model)	6.22	6.18	4.39	4.63	2.83	5.33	5.70
$\hat{\sigma}$ (1st Trunc)	7.19	7.72	7.38	5.58	3.38	6.72	7.88
$\hat{\sigma}$ (2nd Trunc)	6.22	7.45	5.11	5.47	2.83	5.88	5.70
$\overline{Y}$ (Ave. Yield)	73.10	71.86	72.85	76.50	80.00	77.70	54.24

Table 18. Some Statistics for the Iowa and Illinois Corn Yield Models (1949-1973)

The standard deviation of yield about the nitrogen trend is given by:

$$\sigma_{Y,\ NIT} = \{(Y'Y-\hat{\beta}'X'Y)/(n-2)\}^{1/2} \qquad (56)$$

where

$X' = (X_{11}, X_{12}, \ldots, X_{1n})$, and the variable X_{12} is the amount of nitrogen applied during the 2nd year.

The standard deviation of yield about the non-linear trend is given by:

$$\sigma_{Y,\ NLT} = \{(Y_i-\hat{Y}_i)^2/(n-2)\}^{1/2} \quad (57)$$

where

Y_i = the observed yield during the ith year ($i = 1, 2, \ldots, n$), and

$\hat{Y}_i$ = the predicted yield for the ith year (given by the non-linear trend).

There is very little inter-CRD variation of corn yields in Iowa. Whereas, in Illinois the northern and central macro-CRDs yield considerably higher than the southern one. At the state level corn yields in Illinois are about 3.5 bu/acre higher than those in Iowa.

The variation in yield about both the nitrogen trend and non-linear trend is nearly a third smaller than the variation about its mean value. Therefore corn yields in Iowa and Illinois are largely a function of technology. It is interesting to note that nitrogen fertilizer alone accounts for most of the variation in corn yields.

By far, the "best" models developed in this study are for Illinois-North. Both the multiple regression and stepwise models have very small residual variances ($\hat{\sigma}^2$). The models developed for the drier regions (Iowa-West and Illinois-South) are found to have large residual errors.

The truncated models show a general reduction of about one to four bu/acre in the residual variance by the second truncation. Note that for some of the crop regions the second truncation model may coincide with the final model. On the average, the difference in residual variance between the final and second truncation models is well within two bu/acre. Operationally this would mean that the second truncation models are reasonably accurate in estimating the final yield.

E. Sensitivity Analysis of Models

The sensitivity analysis aims at examining the model responses to changes in the number of predictor variables themselves. Such tests will enable the modeler to identify those variables likely to contribute significantly to variations in the yield. In an earlier study Eddy (1978) examined the influence of climate variations on model stability and predicted mean yield. Model inadequacy, often caused by noise in the phenological data shows up in physiologically important variables making insignificant contributions to yield.

Sensitivity analysis tests have been performed on all the state and macro-CRD models. The Iowa-West multiple regression model and Illinois-North stepwise procedure model sensitivity analysis results will now be discussed in detail.

The Iowa-West sensitivity results are shown in Table 19. The significance level for each variable in the complete model are given in Equation (43). The quadratic term for precipitation during the early vegetative stage (P_3Q) is not very significant (.1457), the precipitation variable during one to two weeks after maturity (R_3) is least significant (.7280) at the 5 percent level. An examination of the table shows that nitrogen explains so much of the yield variability that the addition of weather variables does very little to improve the model's predictive ability, note that the residual variance can however be improved. The inclusion of all the variables in the analysis produces the lowest residual variance. The residual variance is improved by 20 percent but uncertainty in the estimate is increased by 20 percent.

VARIABLES IN MODEL							
b_o	NIT	SM3	P_3Q	R_3	$\bar{\hat{y}}$	$\bar{\sigma}_{\hat{y}}$	σ_{RES}
1	1				71.86	2.22	7.72
1	1	1			71.86	2.42	6.91
1	1		1		71.86	4.13	7.45
1	1			1	71.86	4.29	7.82
1	1	1	1	1	71.95	2.80	6.18
1	1	1	1		71.85	2.71	6.71
1	1	1		1	71.87	3.93	6.61
1	1		1	1	71.87	4.57	7.44

Table 19. Iowa-West Multiple Regression Model
Sensitivity Analysis Results

Soil moisture during silking and pollination (SM3) seems to be very important in this drier macro-CRD, as nitrogen and SM3 together produce a better model than that by including all the variables in the analysis. Note that if we drop the insignificant variables (P_3Q and R_3) from the overall model the variance improves. This is to be expected in a forced multiple regression model. The importance of soil moisture in western Iowa is evident from Table 19, the largest variation in yield is produced by omitting this variable from the analysis; the uncertainty in the estimate increases by 106 percent but the residual variance drops by nearly 4 percent.

The Illinois-North stepwise regression model sensitivity analysis results are shown in Table 20. Since this is a stepwise model, all variables are significant at the 5 percent level. The smallest variance in yield is produced by the trend term alone. If only one weather variable were to be included in the model then the percentage of corn not planted by week 21 (PCTNP) is the best choice; the residual variance goes up by 2.3 percent and the uncertainty in the estimate increases by nearly 25 percent. If all the variables are included in the analysis then the residual variance drops by 21.6 percent but the uncertainty in the estimate goes up by 23.89 percent.

VARIABLES IN MODEL					$\bar{\hat{y}}$	$\overline{\sigma_{\hat{y}}}$	σ_{RES}
b_o	NIT	PCTNP	P_1	P_5T90			
1	1				78.98	1.13	3.94
1	1	1			79.98	1.41	4.03
1	1		1		79.98	2.13	3.87
1	1			1	79.98	2.22	3.64
1	1	1	1	1	80.10	1.40	3.09
1	1	1	1		79.97	1.61	3.97
1	1	1		1	79.98	1.44	3.70
1	1		1	1	79.99	1.87	3.01

Table 20. Illinois-North Stepwise Regression Model Sensitivity Analysis Results

If we are to drop only one variable from the model then an examination of Table 20 shows that planting time precipitation (P_1) is the best choice. The uncertainty in the estimate increases by 27.4 percent but the residual variance goes down by 6.1 percent. The variables PCTNP and P_5T90 increase the uncertainty in the estimate by 42.48 and 65.49 percent, respectively.

The Iowa-West multiple regression model has been selected for performing some additional sensitivity tests. The model statistics for the period 1949-1973 are shown in Table 21.

N = 24	$\bar{x}_2 = 50.26$	$\bar{x}_3 = 31.01$	$\bar{x}_4 = .04$	$\bar{x}_5 = 2.25$
	$\sigma_2 = 34.35$	$r_{23} = .37$	$r_{24} = -.31$	$r_{25} = .17$
		$\sigma_3 = 5.03$	$r_{34} = -.01$	$r_{35} = .35$
			$\sigma_4 = 1.07$	$r_{45} = .12$
				$\sigma_5 = 1.90$

Table 21. Iowa-West Multiple Regression Model Statistics for 1949-1973 (1970 Excluded). Note that $x_2 \equiv$ NIT, $x_3 \equiv$ SM3, $x_4 \equiv P_3Q$ and $x_5 \equiv R_3$.

Tests have been run using the above matrix with some of the elements replaced as shown in Table 22. The first four rows were obtained by varying σ_2, σ_3 and σ_4 as indicated. The uncertainty in the yield estimate ($\overline{\hat{\sigma}_Y}$), as well as the residual variance ($\hat{\sigma}^2$) increase with the addition of noise; however, the mean remains unchanged.

Soil moisture at silking (SM3) and nitrogen fertilizer application rate (NIT) are positively correlated ($r_{23} = .37$). The effect of first, reducing to zero and second, doubling the fertilizer soil moisture interaction are also shown in Table 22. The model improves considerably when the two variables are independent ($r_{23} = 0$). But when the two variables are highly correlated ($r_{23} = .74$) large increases in $\overline{\sigma_{\hat{Y}}}$ and $\hat{\sigma}$ are evident.

PERTURBATIONS	$\bar{\hat{Y}}$	$\overline{\sigma_{\hat{Y}}}$	$\hat{\sigma}$
$\sigma_i^2 + .00\ {}_i^2$	71.85	2.71	6.71
$\sigma_i^2 + .01\ {}_i^2$	71.85	2.84	7.03
$\sigma_i^2 + .10\ {}_i^2$	71.85	3.73	9.23
$\sigma_i^2 + .20\ {}_i^2$	71.85	4.40	10.88
$r_{23} = 0.00$	71.85	1.75	4.35
$r_{24} = 0.74$	71.85	3.66	9.06

Table 22. Some Perturbations Introduced into the Elements of the Matrix Shown in Table 21 (Note that in σ_i, i = 2, 3 or 4)

The influence of climate variations on model stability has been studied by using the climatology for the various periods shown in Table 23 to replace the appropriate elements (x_3, x_4, σ_3, σ_4 and r_{34}) of Table 21. A comparison of the first two rows indicates that the model stability is not affected by using average phenophases instead of their annual values. The results indicate that model is very stable ($\hat{\sigma}$ and $\overline{\sigma_{\hat{Y}}}$ are stable) over the several periods investigated. Also, the two variables x_3 (SM3) and x_4 (P_3Q) are found to be independent of one another.

The sensitivity analysis results discussed above aid the modeler in studying the model responses to changes in the number of predictor variables and to changes in their magnitude as well. The selection of variables depends on whether the objective is to minimize the uncertainty in the yield estimate or to merely fit a better regression line.

PERIOD	x_3	x_4	σ_3	σ_4	r_{34}	$\hat{\beta}_3$	$\hat{\beta}_4$	$\overline{\sigma}_{\hat{Y}}$	$\hat{\sigma}$	ΔY	%$\overline{Y}$
1949-1973	31.01	0.04	5.05	1.74	0.02	0.72	1.26	2.71	6.71	0.00	0.00
1949-1973	30.24	-0.17	5.25	2.21	0.04	0.67	0.91	2.74	6.76	-0.82	-1.14
1901-1973	27.96	-0.39	6.43	2.37	-0.003	0.56	0.91	2.71	6.70	-2.74	-3.81
1901-1910	30.48	-0.66	7.66	2.38	-0.08	0.62	1.55	2.43	6.00	-1.26	-1.75
1911-1920	24.82	0.03	5.69	0.90	0.11	0.67	0.07	2.86	7.08	-4.47	-6.22
1921-1930	27.12	-0.31	5.24	1.07	-0.04	0.80	2.83	2.57	6.35	-3.24	-4.51
1931-1940	21.77	0.17	5.74	2.50	0.05	0.66	0.20	2.86	7.07	-6.49	-9.03
1941-1950	30.59	-1.46	4.05	4.52	0.05	0.88	0.14	2.86	7.06	-2.19	-3.05
1951-1960	27.52	0.32	5.67	0.58	0.05	0.59	1.91	2.83	7.00	-2.16	-3.01
1961-1970	31.57	-1.07	3.82	3.22	0.01	0.90	0.54	2.76	6.86	-1.00	-1.39

Table 23. The Influence of Climate Variations on Model Stability. $x_3 \equiv$ SM3 and $x_4 \equiv P_3Q$. The First Line Uses Annual Phenology Dates for x_3 and x_4, Other Periods Use Mean Phenophases. ΔY = Mean Yield Deviation from Line 1 Using Line 1 Regression Coefficients. %$\overline{Y}$ = Average Percent Deviation of Mean Yield from 1949-1973 Period, Excluding 1970. ($\overline{Y}$ = 71.85 bu/acre).

In summary the regression models developed for Iowa and Illinois are based on only 24 years of data. The model results indicate that the coefficients have stabilized during the 1969-1973 period. Independent tests on the models indicate that the models are not very sensitive to the severe drought of 1974. This may be partly due to the enormous emphasis on the nitrogen trend. Results from the sensitivity analyses are well in accordance with observed climate-yield relationships.

CHAPTER V

CONCLUDING SUMMARY

The purpose of this chapter is to summarize the major accomplishments of this study and provide directions for further research in this area of crop-yield modeling. Some of the major accomplishments and conclusions follow.

1) The objective was to develop low cost corn yield models sensitive to weather, phenology and technology at the state and macro-CRD levels for Iowa and Illinois. The models developed are reasonably sensitive to changes in weather during the various phenological stages of the crop. Technological trend is accounted for by the observed statewide nitrogen fertilizer application rates. The regression coefficients for the various model inputs are also shown to make agronomic sense. Such low computer cost models can be easily developed for other regions in the Corn Belt.

2) The use of a phenological time scale has proven to be invaluable in studying climate-yield relationships. Varietal information on corn planted is essential to study climate-yield relationships in a more comprehensive manner.

3) Models based on a technological input, such as nitrogen fertilizer, require that the fertilizer data be reported as accurately as possible, otherwise large residual errors are likely to ccur in the model estimates.

4) Response of corn to nitrogen fertilizer is more pronounced in Illinois than in Iowa. This may be due to the larger available soil moisture reserves in Illinois during the growing season.

5) The dependence of corn yields on weather is clearly indicated by the drought of 1974 in Iowa and Illinois. Technology cannot compensate for yield reductions due to weather particularly during periods of protracted drought. Further, the technology-weather based models have an inherent tendency to overpredict during such years. It should be noted that even during drought years the weather variables account for the usual amount of variation in yield permitted by their coefficients.

6) As a consequence of the interaction between weather and technology, corn yields will be high during those years when weather is favorable and fertilizer inputs are high and vice versa. It is important to realize that corn yields such as those observed in the early 1950's and 1960's are likely to occur under conditions of drought.

7) Supplemental irrigation during drought years will be of little use if the temperature stress during the tasseling, silking and pollination stages is not relieved.

8) The study has conclusively shown that the signal to noise ratio (γ) is a better measure of model weather sensitivity than the R^2 value.

Further research in weather-phenology-technology related corn yield modeling should consider the following:

a) If corn yield models are to have an economic value, they should estimate yield accurately during drought years. This would require that the modeler give more weight to the weather inputs. The inclusion of a trend term in the analysis has its limitations.

b) Future models should aim at accounting for the technological trend in an explicit manner, so that the weather variables will have to account for a larger variation about the mean yield.

c) Varietal information on corn and phenological data should be obtained to make a more sensible use of the crop calendar concept, and

d) The non-linear interaction between nitrogen fertilizer and precipitation at planting has to be taken into account by future models.

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APPENDIX

JACKKNIFE AND BOOTSTRAP TEST RESULTS

IOWA STATE JACKKNIFE TESTS (1963-1973) FOR MODEL 2.

YEAR	B0	B1	B2	YIELD	YHAT	RESID
1963	47.19	0.53	0.29	80.00	73.38	6.62
1964	47.52	0.53	0.33	77.50	70.02	7.48
1965	47.93	0.52	0.34	82.00	78.50	3.50
1966	47.97	0.52	0.34	89.00	86.95	2.05
1967	47.82	0.53	0.33	88.50	89.79	-1.29
1968	47.27	0.55	0.33	93.00	105.33	-12.33
1969	47.45	0.54	0.35	99.00	108.24	-9.24
1971	47.93	0.52	0.33	102.00	101.01	0.99
1972	48.21	0.51	0.31	116.00	107.91	8.09
1973	47.99	0.52	0.33	107.00	105.41	1.59

IOWA STATE BOOTSTRAP TESTS (1963-1973) FOR MODEL 2.

YEAR	B0	B1	B2	YIELD	YHAT	RESID
1963	35.99	0.96	0.25	80.00	79.64	0.36
1964	35.92	0.96	0.25	77.50	78.15	-0.65
1965	36.15	0.95	0.25	82.00	95.64	-13.64
1966	40.97	0.77	0.31	89.00	100.36	-11.36
1967	43.91	0.67	0.34	88.50	98.24	-9.74
1968	45.71	0.61	0.36	93.00	110.09	-17.09
1969	47.94	0.52	0.32	99.00	106.36	-7.36
1971	48.63	0.49	0.30	102.00	98.63	3.38
1972	48.43	0.50	0.30	116.00	106.91	9.09
1973	47.99	0.52	0.33	107.00	105.41	1.59

Table 24. Jackknife and Bootstrap Tests for Iowa State Stepwise Procedure Model. (See eq. (41), pg. 91).

IOWA WEST JACKKNIFE TESTS (1963-1973) FOR MODEL 2.

YEAR	B0	B1	B2	B3	B4	YIELD	YHAT	RESID
1963	22.63	0.56	0.90	1.52	-3.40	77.71	65.70	12.01
1964	22.99	0.56	0.90	1.50	-3.17	76.22	75.67	0.55
1965	22.41	0.56	0.92	1.48	-3.25	80.04	77.79	2.25
1966	22.58	0.56	0.92	1.48	-3.20	89.62	88.49	1.13
1967	21.81	0.56	0.88	3.29	-2.88	86.54	69.57	16.97
1968	20.92	0.59	0.85	1.63	-1.91	89.47	104.80	-15.33
1969	21.85	0.56	0.92	1.45	-3.10	101.04	104.58	-3.54
1971	22.72	0.57	0.91	1.62	-3.30	99.84	104.66	-4.82
1972	23.76	0.55	0.87	1.44	-3.10	116.32	113.10	3.22
1973	22.39	0.54	0.94	1.43	-3.20	108.48	102.85	5.63

IOWA-WEST BOOTSTRAP TESTS (1963-1973) FOR MODEL 2.

YEAR	B0	B1	B2	B3	B4	YIELD	YHAT	RESID
1963	5.97	1.45	0.86	3.79	-1.05	77.71	91.20	-13.49
1964	4.79	1.08	0.86	1.65	-0.94	76.22	84.51	-8.29
1965	7.62	1.00	0.80	2.98	-0.44	80.04	95.69	-15.65
1966	10.70	0.80	0.92	2.92	-1.09	89.62	100.95	-11.33
1967	12.67	0.70	0.95	2.84	-1.19	86.54	80.95	5.59
1968	12.46	0.70	0.96	2.21	-1.21	89.47	114.65	-25.18
1969	21.87	0.56	0.93	1.44	-3.03	101.04	105.22	-4.18
1971	23.17	0.54	0.90	1.42	-3.09	99.84	102.09	-2.25
1972	23.50	0.53	0.89	1.32	-2.98	116.32	111.58	4.74
1973	22.39	0.54	0.94	1.43	-3.22	108.48	102.80	5.68

Table 25. Jackknife and Bootstrap Tests for Iowa-West Stepwise Procedure Model. (See eq. (44), pg. 95).

IOWA EAST JACKKNIFE TESTS (1963-1973) FOR MODEL 2.

YEAR	B0	B1	B2	B3	B4	B5	B6	YIELD	YHAT	RESID
1963	58.92	0.57	-0.12	3.60	-4.80	0.36	-2.12	82.38	67.94	14.44
1964	61.53	0.54	-0.13	2.67	-4.90	0.45	-2.30	76.33	73.30	3.03
1965	62.54	0.54	-0.14	2.63	-5.26	0.46	-2.40	83.20	78.99	4.21
1966	62.28	0.55	-0.14	2.81	-5.19	0.44	-2.50	86.58	88.12	-1.54
1967	63.39	0.55	-0.14	2.29	-5.64	0.44	-2.60	87.48	92.72	-5.24
1968	60.46	0.57	-0.17	2.93	-4.30	0.44	-2.51	93.89	103.62	-9.73
1969	63.76	0.54	-0.15	3.12	-5.72	0.45	-2.85	92.91	88.56	4.35
1971	62.99	0.56	-0.16	3.05	-5.48	0.45	-2.80	104.07	109.13	-5.06
1972	63.01	0.52	-0.21	2.64	-4.71	0.42	-2.16	113.90	100.47	13.43
1973	62.12	0.55	-0.14	2.84	-5.16	0.44	-2.49	103.41	103.68	-0.27

IOWA-EAST BOOTSTRAP TESTS (1963-1973) FOR MODEL 2.

YEAR	B0	B1	B2	B3	B4	B5	B6	YIELD	YHAT	RESID
1963	56.44	0.74	-0.24	5.79	-4.94	0.30	-3.05	82.38	64.72	17.66
1964	56.92	0.78	-0.23	3.23	-4.77	0.36	-3.02	76.33	81.59	-5.26
1965	56.55	0.71	-0.21	2.67	-4.00	0.38	-2.35	83.20	86.69	-3.49
1966	59.04	0.66	-0.22	2.59	-4.38	0.40	-2.39	86.58	93.63	-7.05
1967	61.87	0.59	-0.25	2.65	-4.60	0.42	-2.57	87.48	94.28	-6.80
1968	62.39	0.57	-0.26	3.50	-4.54	0.43	-2.72	93.89	104.32	-10.43
1969	67.25	0.51	-0.26	3.43	-6.07	0.44	-3.06	92.91	83.60	9.31
1971	63.60	0.52	-0.22	2.73	-4.88	0.43	-2.35	104.07	106.50	-2.43
1972	63.35	0.51	-0.22	2.52	-4.66	0.42	-2.18	113.90	98.84	15.06
1973	62.12	0.55	-0.14	2.84	-5.16	0.44	-2.49	103.41	103.68	-0.27

Table 26. Jackknife and Bootstrap Tests for Iowa-East Stepwise Procedure Model.
(See eq. (46), pg. 97).

ILLINOIS STATE JACKKNIFE TESTS (1963-1973) FOR MODEL 1.

YEAR	B0	B1	B2	B3	B4	B5	YIELD	YHAT	RESID
1963	83.79	0.43	-2.00	2.21	0.43	-0.26	87.00	80.29	6.71
1964	100.91	0.43	-2.72	2.13	0.41	-0.30	80.00	80.17	-0.17
1965	98.83	0.42	-2.64	1.98	0.41	-0.29	94.00	89.28	4.72
1966	94.18	0.45	-1.70	1.19	-0.09	-0.44	82.00	95.26	-13.26
1967	102.00	0.42	-2.79	2.05	0.41	-0.29	104.00	102.06	1.94
1968	107.80	0.44	-3.42	2.36	0.60	-0.19	90.00	104.33	-14.33
1969	102.75	0.42	-2.69	2.82	0.34	-0.33	102.00	96.43	5.57
1971	92.31	0.42	-2.40	2.14	0.45	-0.26	106.00	101.35	4.65
1972	103.66	0.42	-2.82	2.02	0.39	-0.32	110.00	107.13	2.87
1973	99.57	0.43	-2.68	2.15	0.41	-0.30	103.00	105.32	-2.32

ILLINOIS STATE BOOTSTRAP TESTS (1963-1973) FOR MODEL 1.

YEAR	B0	B1	B2	B3	B4	B5	YIELD	YHAT	RESID
1963	83.37	0.53	-1.73	0.92	0.14	-0.29	87.00	84.32	2.68
1964	91.23	0.54	-2.02	0.73	0.09	-0.32	80.00	83.79	-3.79
1965	92.29	0.52	-2.12	0.67	0.14	-0.32	94.00	93.24	0.76
1966	92.33	0.52	-2.11	0.68	0.14	-0.33	82.00	98.25	-16.25
1967	101.84	0.45	-3.27	2.30	0.66	-0.15	104.00	103.30	0.70
1968	101.49	0.45	-3.26	2.34	0.66	-0.15	90.00	104.76	-14.76
1969	96.18	0.41	-2.41	2.78	0.37	-0.31	102.00	95.69	6.31
1971	94.24	0.42	-2.47	2.02	0.44	-0.27	106.00	101.56	4.44
1972	102.20	0.42	-2.77	2.04	0.40	-0.31	110.00	107.13	2.87
1973	99.57	0.43	-2.68	2.15	0.41	-0.30	103.00	105.32	-2.32

Table 27. Jackknife and Bootstrap Tests for Illinois State Multiple Regression Model. (See eq. (47), pg. 98).

ILLINOIS-NORTH JACKKNIFE TESTS (1963-1973) FOR MODEL 2.

YEAR	B0	B1	B2	B3	B4	YIELD	YHAT	RESID
1963	61.86	0.39	-0.12	-1.51	0.45	82.75	88.98	-6.23
1964	61.74	0.39	-0.12	-1.54	0.34	85.75	87.02	-1.27
1965	61.59	0.39	-0.12	-1.53	0.33	91.45	89.22	2.23
1966	60.97	0.39	-0.11	-1.37	0.32	88.50	90.50	-2.00
1967	61.46	0.39	-0.12	-1.44	0.32	100.70	99.74	0.96
1968	61.85	0.40	-0.11	-1.75	0.31	95.05	99.90	-4.85
1969	61.68	0.39	-0.11	-1.54	0.34	104.45	103.06	1.39
1971	61.57	0.39	-0.12	-1.52	0.33	103.05	102.79	0.26
1972	61.68	0.39	-0.11	-1.55	0.33	107.95	107.41	0.54
1973	61.59	0.39	-0.12	-1.52	0.33	99.50	99.53	-0.03

ILLINOIS-NORTH BOOTSTRAP TESTS (1963-1973) FOR MODEL 2.

YEAR	B0	B1	B2	B3	B4	YIELD	YHAT	RESID
1963	60.26	0.43	-0.13	-1.38	0.39	82.75	89.50	-6.75
1964	60.52	0.41	-0.11	-1.48	0.27	85.75	87.05	-1.30
1965	60.63	0.41	-0.10	-1.47	0.27	91.45	90.33	1.12
1966	60.29	0.42	-0.10	-1.44	0.26	88.50	92.84	-4.34
1967	61.86	0.40	-0.10	-1.75	0.31	100.70	101.04	-0.34
1968	61.86	0.40	-0.10	-1.75	0.31	95.05	100.06	-5.01
1969	61.94	0.38	-0.10	-1.60	0.34	104.45	101.98	2.47
1971	61.67	0.39	-0.11	-1.55	0.33	103.05	102.83	0.22
1972	61.70	0.39	-0.11	-1.56	0.33	107.95	107.39	0.56
1973	61.59	0.39	-0.12	-1.52	0.33	99.50	99.53	-0.03

Table 28. Jackknife and Bootstrap Tests for Illinois-North Stepwise Procedure Model. (See eq. (50), pg. 107).

ILLINOIS-CENTRAL JACKKNIFE TESTS (1963-1973) FOR MODEL 2.

YEAR	B0	B1	B2	B3	B4	YIELD	YHAT	RESID
1963	29.90	0.50	0.63	-2.66	1.90	85.86	81.53	4.33
1964	29.94	0.50	0.62	-2.66	2.10	80.80	81.59	-0.79
1965	33.04	0.49	0.63	-3.18	1.05	98.16	88.07	10.09
1966	35.29	0.52	0.47	-2.86	1.55	81.40	96.08	-14.68
1967	29.53	0.48	0.62	-2.80	2.60	106.92	95.60	11.32
1968	28.41	0.51	0.61	-1.61	1.81	90.50	101.04	-10.54
1969	28.89	0.51	0.66	-2.82	2.12	105.16	111.67	-6.51
1971	28.94	0.48	0.62	-2.32	2.36	110.98	100.50	10.48
1972	29.70	0.50	0.62	-2.75	2.24	113.60	115.82	-2.22
1973	28.47	0.50	0.66	-2.63	2.07	107.86	111.68	-3.82

ILLINOIS-CENTRAL BOOTSTRAP TESTS (1963-1973) FOR MODEL 2.

YEAR	B0	B1	B2	B3	B4	YIELD	YHAT	RESID
1963	33.67	0.58	0.51	-2.88	0.71	85.86	82.56	3.30
1964	32.51	0.60	0.49	-2.88	1.18	80.80	86.28	-5.48
1965	31.16	0.58	0.55	-2.47	1.06	98.16	94.23	3.93
1966	29.07	0.59	0.55	-2.23	1.56	81.40	99.06	-17.66
1967	25.47	0.50	0.67	-1.81	2.54	106.92	97.87	9.05
1968	23.62	0.54	0.72	-1.48	2.00	90.50	104.32	-13.82
1969	26.66	0.51	0.69	-2.70	2.45	105.16	111.36	-6.20
1971	28.03	0.49	0.65	-2.36	2.37	110.98	101.50	9.48
1972	28.29	0.51	0.66	-2.77	2.23	113.60	116.52	-2.92
1973	28.47	0.50	0.66	-2.63	2.07	107.86	111.68	-3.82

Table 29. Jackknife and Bootstrap Tests for Illinois-Central Stepwise Procedure Model. (See eq. (52), pg. 110).

ILLINOIS-SOUTH JACKKNIFE TESTS (1963-1973) FOR MODEL 1.

YEAR	B0	B1	B2	B3	B4	B5	B6	YIELD	YHAT	RESID
1963	29.05	0.37	-0.58	2.34	0.74	-0.71	-0.68	68.95	57.56	11.39
1964	29.63	0.37	-0.92	2.48	0.82	-0.65	-1.13	52.20	57.93	-5.73
1965	29.60	0.37	-0.77	2.43	0.80	-0.69	-0.97	69.60	68.67	0.93
1966	31.54	0.37	-0.70	2.28	0.71	-0.73	-0.99	58.00	63.52	-5.52
1967	31.24	0.34	-0.83	1.90	0.72	-0.56	-1.45	89.48	76.21	13.27
1968	29.87	0.36	-0.82	2.44	0.81	-0.71	-1.03	70.40	69.20	1.20
1969	31.46	0.36	-0.90	3.76	0.82	-0.81	-1.15	66.00	52.57	13.43
1971	32.30	0.32	-0.85	2.60	0.79	-0.85	-1.15	70.25	81.11	-10.86
1972	30.44	0.36	-0.73	2.39	0.80	-0.74	-1.00	82.10	77.85	4.25
1973	28.34	0.39	-0.76	2.73	0.79	-0.71	-0.67	70.20	81.47	-11.27

ILLINOIS-SOUTH BOOTSTRAP TESTS (1963-1973) FOR MODEL 1.

YEAR	B0	B1	B2	B3	B4	B5	B6	YIELD	YHAT	RESID
1963	32.38	0.50	-0.42	1.58	0.40	-0.83	-0.21	68.95	60.86	8.09
1964	32.48	0.55	-0.67	1.70	0.42	-0.87	-0.29	52.20	62.39	-10.19
1965	33.35	0.50	-0.45	1.88	0.45	-0.92	-0.32	69.60	73.51	-3.91
1966	33.38	0.47	-0.42	2.09	0.46	-0.90	-0.38	58.00	72.32	-14.32
1967	33.89	0.38	-0.89	4.36	0.76	-0.97	-1.10	89.48	84.55	4.93
1968	33.42	0.40	-0.90	4.87	0.78	-1.05	-0.88	70.40	72.17	-1.77
1969	34.01	0.40	-0.93	4.97	0.79	-1.07	-0.95	66.00	45.67	20.33
1971	31.18	0.41	-0.81	2.99	0.77	-0.90	-0.76	70.25	83.18	-12.93
1972	28.74	0.39	-0.72	2.69	0.79	-0.73	-0.68	82.10	80.23	1.87
1973	28.36	0.39	-0.76	2.73	0.79	-0.71	-0.67	70.20	81.49	-11.29

Table 30. Jackknife and Bootstrap Tests for Illinois-South Multiple Regression Model. (See eq. (53), pg. 111).