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S. E. Hollinger and S. A. Changnon

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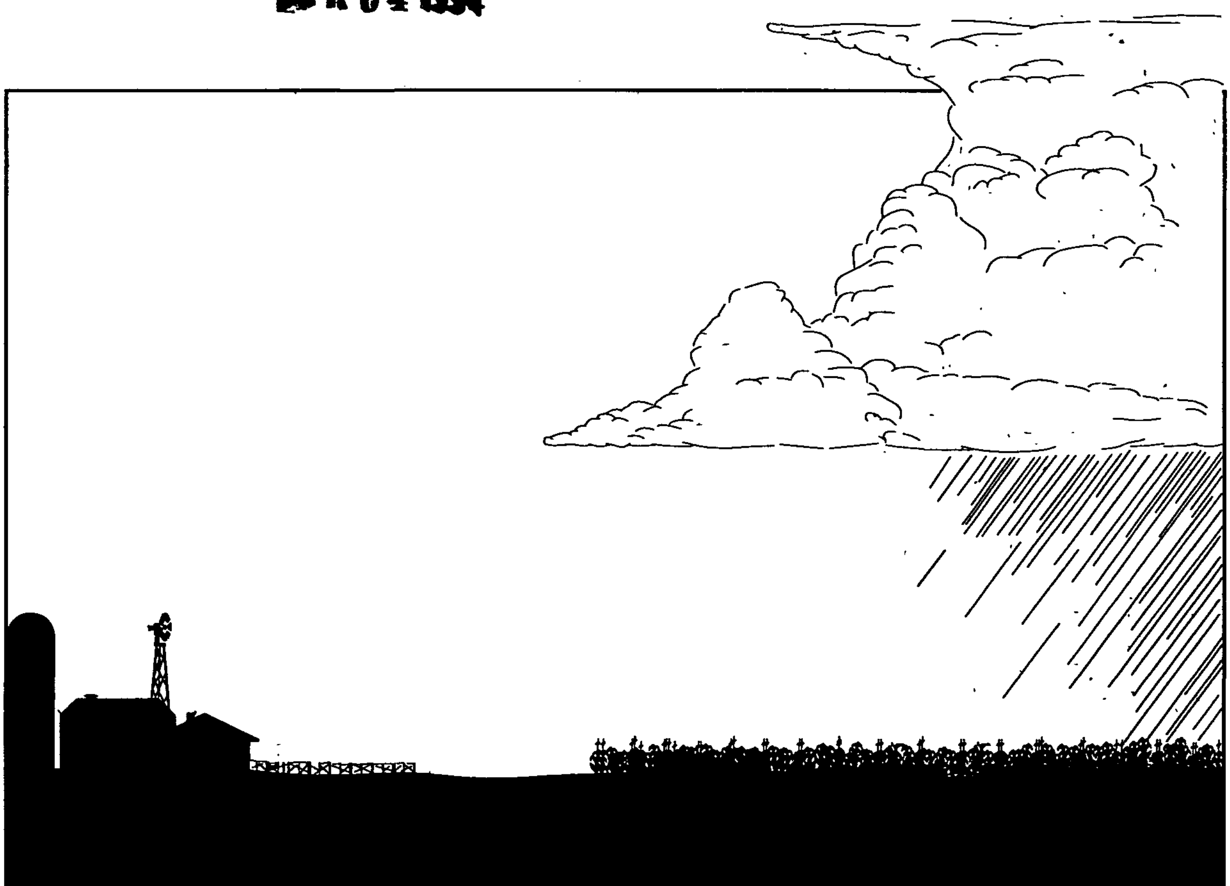

Illinois State Water Survey, Champaign, Illinois 61820

BULLETIN 73

Response of Corn and Soybean Yields to Precipitation Augmentation, and Implications for Weather Modification in Illinois

by

Steven E. Hollinger and Stanley A. Changnon

Title: Response of Corn and Soybean Yields to Precipitation Augmentation, and Implications for Weather Modification in Illinois.

Abstract: Determining the feasibility of weather modification involves two questions: Is it possible to modify the weather and increase rainfall? Will weather modification benefit society? The work reported here is designed to answer the second question: Will weather modification in Illinois benefit agriculture? The objectives of the study were to learn how additional rainfall in typical dry, average, and wet summers would affect corn (Zea *mays*) and soybean *(Glycine max)* yields, and the feasibility of different weather modification programs in actual Illinois summers.

Two field studies were conducted during the summers of 1987-1991. The first was to determine how 25 percent rain increases during typical dry, average, and wet summers would affect corn and soybean yields. The other was to determine how increases of 10, 25, and 40 percent would affect yields. The results of the last study were used in a simulation study to evaluate the potential economic benefit of weather modification to Illinois agriculture.

Results of the first field study show that both corn and soybeans will benefit from increased rainfall from weather modification. However, early-season temperature plays an important role in determining final yields. The second study showed that corn responded best to 40 percent rainfall increases to rain events greater than 25.4 millimeters. Soybeans yields were best with no additions to natural rainfall. The simulation study showed that economic benefit is greatest when weather modification is conducted using early-June season forecasts. This benefit is achieved even without perfect seasonal forecasts.

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Indexing Terms: Weather modification, corn, soybeans, Zea mays, Glycine max, precipitation, temperature.

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CONTENTS

RESPONSE OF CORN AND SOYBEAN YIELDS TO PRECIPITATION AUGMENTATION, AND IMPLICATIONS FOR WEATHER MODIFICATION IN ILLINOIS

by
Steven E. Hollinger and Stanley A. Changnon

EXECUTIVE SUMMARY

Illinois State Water Survey weather modification studies since 1970 have focused on developing a technology to enhance rainfall in Illinois and studying how that increased rainfall might impact Illinois agriculture and water resources. The effects of added rainfall on crop production were initially defined using weather-crop yield models. The availability of agricultural test plots where rainfall could be controlled offered an opportunity to better define the effects of added rain on major crops. The objective of this study was to determine how additional rainfall in a series of summers would impact corn (*Lea mays)* and soybean *(Glycine max)* yields in Illinois. The ultimate goal was to determine the feasibility of different weather modification programs in actual Illinois summers.

Two types of experiments were conducted each year from 1987 through 1991. In one experiment, corn and soybeans were grown in plots that could be covered to keep natural rain off the crops. The crops were exposed to the natural environment whenever it was not raining. During the months of June, July, and August, all natural rain was kept off the crops, and water treatments were applied at rates and on days that simulated typical dry, average, and wet summers, plus increases of 25 percent to the typical dry, average, and wet summer rain regimes.

In the other field experiment, corn and soybeans were grown in an open area under natural conditions where the plots received natural rainfall. At the end of each rainfall event, additional water was applied to the crop to simulate the effects of different weather modification capabilities. Ten different treatments, selected to reflect various potential cloud seeding capabilities, were applied: natural rainfall; 10, 25, and 40 percent increases to all rain events; 10, 25, and 40 percent increases to moderate rain events [rains greater than 2.54 millimeters (mm) up to 25.4 mm]; 10 and 40 percent increases to heavy rain events (rains greater than 25.4 mm); and 40 percent increases to light rain events (rains less than 2.54 mm).

Cultural practices used to grow the corn and soybean crops were typical of those used in east-central Illinois. At maturity the crops were harvested and final grain yield was determined. The yield components that made up the final yield were also measured and studied to determine their response to rainfall during different growth stages.

Additional water applications in the typical dry, average, and wet summers resulted in increased corn and soybean yields. Generally, as the total summer rainfall increased, the final yield increased. An unexpected finding in the study was that corn yields varied more between years than within years under the same water treatments. Soybean yields did not vary as much between and within years as did corn.

Analysis of the year-to-year corn yield variations showed that temperature during the period from planting to tassel initiation (the first 20 to 30 days after planting) was related to final yield. Warmer temperatures during this early growth period resulted in lower yields.

During the summers of 1989 to 1991, corn was planted on two different planting dates and at two plant densities. While population did not have an effect on final yield, corn yields from later planting dates were lower than those from earlier planting dates. Temperature during the early growth stage was correlated to the yields resulting from the two planting dates in the three years. Early growing-season temperature had a greater effect on final yield than did the amount of water received by the plant during the growing season.

The best rainfall enhancement treatment for corn in the open-area experiment, as determined by consistently high yields across all years of the experiment, was 40 percent additional water applied to light or heavy rains. The best treatment for soybeans was natural rainfall and 40 percent increases to all moderate rains.

Integration of these results with climatic, economic, and legal factors affecting rainfall enhancement showed that expected yield increases would be less than those calculated from the five-year open-area experiment. A 25 percent rain increase on days with moderate rains would amount to only 20 percent of the total yield increase observed in the open-area study. With a 25 percent rainfall increase on all rain days, the expected yield increase would be only 43 percent of the experimental increase. The reduction in yields from the experimental increases are due to limitations in weather modification techniques, i.e., the inability to take advantage of seedable events occurring at night and during severe weather conditions.

Results of the rain shelter and open-area experiments have led to the recommendations outlined below:

1. Additional studies need to be conducted to determine the cause of the response of corn to early-season temperature. If the observed response has a physical or physiological explanation, an early-season estimate of final yield potential could be obtained and used in defining the appropriate weather modification program for each summer.
2. The design of the rain shelter experiments did not allow for the identification of the stage of corn growth that results in the greatest yield benefit to the crop. Therefore, additional experiments need to be conducted to identify the optimal time to apply additional water to the corn crop.
3. The 1987-1991 results of the open-area study do not encourage the use of cloud seeding to achieve major yield increases in the deep-soil areas of Illinois and the Corn Belt. The results of this research indicate that with current constraints relating to night seeding and severe weather conditions, only marginal benefits could be produced, except in the occasional drier summers.
4. Existing climatological- or statistical-based techniques to predict regional summer-season rainfall (above normal, near normal, or below normal) should be used on a continuing year-to-year basis to decide on the need for cloud seeding. The capability of predicting the level of summer precipitation by early June is needed in deciding which rain treatment to employ. Knowledge of future hot dry conditions would call for seeding of all possible rain events. Knowledge of near-normal rain conditions would call for seeding only moderate to heavy rains during critical crop periods from late June to early August, depending on the crop's stages. Knowledge of an upcoming wet summer would preclude the use of any rain enhancement.
5. Seeding techniques should be developed that allow for the delivery of seeding material into nighttime convective clouds.
6. A cloud seeding technology needs to be developed that is capable of increasing summer rainfall by 25 percent or more.

INTRODUCTION

This report presents results of an extensive study conducted in central Illinois from 1987 through 1991 to determine how weather and specifically precipitation enhancement affect corn and soybean crops. The objectives of this study were 1) to evaluate the effects of 25 percent increases of water during typical dry, average, and wet summer rainfall regimes on corn and soybean yields and their yield components; 2) to determine how 10, 25, and 40 percent increases to naturally occurring rainfall would impact corn and soybean yields over a series of years; and 3) to determine how the findings relate to ongoing research on cloud and rain modification and cloud seeding for agricultural benefit in Illinois.

This report also includes 1) a review of key findings from past research on corn and soybean responses to rainfall and temperature; 2) a description of the field plot research conducted in central Illinois for this study; 3) results of those field plot studies; 4) corn and soybean yield responses to different water treatments and the natural weather during the five years of data collection, 1987 to 1991;5) discussion of how the timing of the rainfall and temperature affected the corn and soybean yield components; and 6) discussion of how the results relate to weather modification experimentation and cloud seeding to enhance crop yields. The report also serves as the third part of an annual report for 1991-1992 to the National Oceanic and Atmospheric Administration (NOAA).

Background

After the initial two decades of weather modification research, 1950 to 1970, **definitive** information about the physical-environmental effects and socioeconomic impacts of purposeful weather modification was still lacking. The early national research objectives rested on a belief that the ability to modify weather would be beneficial, with essentially all winners and no losers.

After two decades, this general perception came under question. The environmental movement of the late 1960s asked probing questions about all forms of environmental modification and its consequences. Federal spending on weather modification research totaled $80 million from 1956 to 1970, but practically no resources had been devoted to analyzing the impacts on the hydrologic cycle, biological systems, agriculture, or society.

Then came questions from the Office of Management and Budget, the General Accounting Office, Congress, and elsewhere about federal expenditures for weather modification research. They could not be answered with results from credible environmental and economic studies. All too often, economic analyses were very simplistic. For example, an inch of rain in July was declared to be worth 50 million bushels of corn; with corn priced at $3 a bushel, this amounted to $150 million. Economists and environmentalists in Washington were not convinced by such analyses. In fact, these approaches raised deeper questions about the adequacy of weather modification research.

The two basic questions mat should have been addressed independently from the beginning were: "Will weather modification work?" and "Is it worth doing?" Unfortunately, only the first question was being addressed. When the answers even to that question were not forthcoming, for a variety of complex scientific and technical reasons, it became extremely important to answer the value question adequately to justify further federal expenditures.

The Illinois State Water Survey (ISWS), the state's lead atmospheric resources research agency, concluded in 1969 that it was necessary to assess the potential of weather and precipitation modification in Illinois. The Survey already had the benefit of past scientific endeavors and errors to guide it. Thus, the ongoing Illinois effort began by addressing the impact assessment problems. This paper presents the most recent research results in answer to the question, "Is weather modification worth doing?"

The early Water Survey research on this question looked into three areas: the effects on water resources and on agriculture, the two most weather-sensitive elements in Illinois, and on state policy issues related to weather modification. Research during 1969-1974 (Changnon and Huff, 1979) revealed that potential benefits to the state's water resources were negligible unless precipitation could be enhanced significantly during droughts. But further research showed that the ability to produce meaningful precipitation increases during droughts was unlikely. However, research into agricultural effects revealed that enhanced summer rainfall at critical times during the growing season could benefit corn and soybeans (Huff and Changnon, 1972). Research on policy issues led to model legislation to control and regulate purposeful cloud seeding projects in the state.

Separate agricultural research during 1969-1973 focused on the use of crop yield-weather regression models (Huff and Changnon, 1972). Models were developed at county and regional levels to assess the effects of altered monthly and seasonal precipitation on yields. These regression models showed that summer rainfall increases of 25 percent would increase corn yields 5 to 10 percent, enough to justify the cost of a then-typical cloud seeding project with a sizeable profit. Benefit-cost ratios would be about 5:1.

This information became critical in guiding the weather modification research of the Illinois State Water Survey. Similar assessments related to hail suppression (Changnon and

Morgan, 1976). But results showed that without an extremely high-performance technology, such as the ability to reduce hail by 60 percent or more, the benefit-cost ratio would be negligible. This capability was viewed as scientifically very unlikely. The hail suppression research results, coupled with the agricultural rain research results, helped focus Water Survey cloud seeding research after 1976 on the study of **summer rainfall enhancement.**

In 1978 the ISWS launched the "Precipitation Augmentation for Crops Experiment" (PACE). Designed in conjunction with agricultural scientists at the University of Illinois, Michigan State University, Ohio State University, and Purdue University, the experiment would explore the potential for summer rainfall enhancement and study rainfall effects. Since 1985 the effects studies have focused on definitive analyses of the effects of altered rainfall on the hydrologic cycle, on crop growth processes and yields, and on the economy.

A three-year project on the economic value of a workable cloud seeding capability in Illinois and the Midwest led to the development of a major econometric feed-livestock model for the nation (Offutt et al., 1987; Garcia et al., 1990). This laid the groundwork for research on the impacts of different precipitation changes at the crop district, state, and regional levels, and on the agricultural economy of the nation. This model utilized weather-yield regressions based on data for the late 1970s and 1980s. During the same period, a basin-scale, four-layer hydrologic model (Durgunoglu et al., 1987) was developed. This allowed assessment of the daily distribution of rainfall amounts within the hydrologic cycles of typical Illinois basins.

A third essential area of investigation was to reassess the crop-weather relationships defined in 1969-1974 and the predicted yield benefits from added rainfall. By 1986, 15 years after the earlier research, agricultural practices had changed significantly in Illinois, increasing grain yields and affecting crop-weather relationships. The relationships between rain changes and crop behavior had to be redefined and refined with more precise information.

Crop Yield Responses to Weather

The year-to-year variability of corn and soybean yields is primarily due to the effects of the growing-season weather. The most obvious weather influences on crop yields are precipitation and temperature during the growing season. However, more spatially uniform weather variables, such as solar radiation and relative humidity, can also impact crop yields, as can the timing of unfavorable weather during the growing season. This section reviews the findings of some of the numerous studies on the effects of weather on corn and soybean yields.

Corn

Efforts to quantify the effects of weather on corn yield *(Zea mays* L.) have included regression and physiological models (Runge, 1968; Offutt et al., 1987; Thompson, 1986; Muchow et al., 1990) and field plot and growth chamber studies (Denmead and Shaw, 1960; Benoit et al., 1965; Herrero and Johnson, 1981; Harder et al., 1982; Ouattar et al., 1987a,b; Grant et al., 1989). These studies focused on the effects of temperature and rainfall either throughout the growing season (modeling studies) or during specific growth stages (plot or growth chamber studies).

The regression models used data from the U.S. Department of Agriculture (USDA) Statistical Reporting Service to relate temperature and rainfall to corn and soybean yields over areas the size of a county or larger. Thompson (1986) found **that the** highest corn yields were associated with normal preseason precipitation, above-normal July and August rainfall, normal June temperature, and below-normal temperature in July and August. Using a physiologically- based model, Muchow et al. (1990) reported that temperature affected growth duration: lower temperatures increased the time a crop could intercept radiation, and as growth duration increased, so did yield.

Com yields are determined by a number of components that can be affected by management practices and weather at different times. Those components include plant density, the number of rows per ear, the number of kernels per row, and kernel mass.

Plant density is determined for the most part during the period from planting to one week after emergence. After this period, additional stand losses may be due to insect and disease attacks, although these are generally small. The number of rows per ear is determined during the period from ear initiation to the end of row set, generally while the corn plant is in the six- to ten-leaf stage (Hollinger, 1981). The number of kernels per row is determined from ear initiation to silking, and kernel mass is determined from silking to maturity.

Plant density is determined to a great extent by the density of seeds planted. But density is modified to some extent by soil moisture and temperature during the germination and emergence of the young plants. Generally, yields will increase as plant density increases to an optimal population. Beyond this point, the plants must compete for water and nutrients, and yields will decline due to individual plant yield reductions. At these higher densities, yield reductions occur in the form of increased barrenness (plants without ears or partially formed ears), reduced numbers of rows per ear, reduced numbers of kernels per row, and reduced kernel mass.

The total number of kernels per plant (determined by the number of rows per ear and kernels per row) and kernel mass can also be reduced by unfavorable weather during different parts of the growing season. For example, the number of rows per ear is determined approximately 30 to 40 days after planting (Hollinger, 1981). Stresses due to weather and/or plant competition during this period may reduce the numbers of rows per ear.

The potential total number of kernels per row, and thus the potential total number of kernels per ear, is determined during the period beginning 30 days after planting until approximately two weeks after pollination. Before pollination, the plant is developing the kernel primordia, which determine the maximum number of kernels that will eventually be on the ear. Eck (1986) studied the effects of water stress during various corn growth stages and found that water deficits imposed 41 days after planting reduced leaf, stalk, and ear yields, while those imposed 55 days after planting reduced only stalk and ear yields. While the most visible corn growth during the first 55 days was vegetative, the ear was being formed. Thus, water deficits during vegetative growth reduced kernel numbers, although they had little effect on weight per kernel (Eck, 1986).

Vegetative growth ends when the tassel emerges. At this time all the leaves on the plant are fully developed and the stalk stops growing. Shortly after tassel emergence, silks normally appear at the top of the ear and pollen is shed from the tassels. Temperature and water stresses during pollination and the two weeks following can result in significant yield losses. Research has shown that high air temperature (>35°C) during pollination resulted in pollen blasting and desiccation (Herrero and Johnson, 1980). During the first two weeks following pollination, the lag phase, air temperatures <15°C or >25°C reduced corn yields by reducing endosperm cell formation and starch granule numbers (Jones et al., 1981, 1984, 1985).

Generally, kernel numbers are not affected by water deficits during grain filling unless severe deficits are imposed early in the period (Eck, 1986). The period most sensitive to water stress begins with silking and extends to 22 days afterward (Grant et al., 1989). Herrero and Johnson (1981) reported that water stress during the period that silks are appearing caused yield loss because of a reduced rate of silk elongation.

Water stress during the lag phase and grain fill periods reduces the number of endosperm cells formed during kernel development (Ouattar et al., 1987a) and the length of the grain fill period itself (Ouattar et al., 1987b). These stresses result in smaller kernels, but they do not affect final kernel number.

Soybeans

Numerous field plot, greenhouse, and growth chamber studies have been conducted to determine the response of soybean varieties to the timing and severity of water and temperature stresses. Soil moisture stress throughout the growing season results in reduced leaf area, leaf duration, crop growth rate, shoot dry matter (Pandey et al., 1984b), number of pods per square meter, and number of seeds per pod (Pandey et al., 1984a). The single yield component most sensitive to drought stress is the number of pods (Cox and Jolliff, 1986). Of the yield components, seed weight is least affected by drought. Seed weight differences are the result of a shortened seed fill period, rather than a reduction in the rate of seed fill (Meckel et al., 1984). The effect of moisture stress on soybean yields is variety-dependent. Absolute yield reductions range from 1.0 megagram per hectare (Mg/ha) or 14.9 bushels per acre (bu/ac) in the most sensitive varieties to 0.2 Mg/ha (3.0 bu/ac) in the least sensitive varieties (Mederski and Jeffers, 1973).

Adequate water is generally required after full bloom and during the pod fill stage for maximum yields (Doss et al., 1974). Some studies have shown that stresses throughout flower induction and pod elongation have the greatest effects on final soybean yields. Sionit and Dramer (1977) found that water stress during flower induction and flowering resulted in fewer flowers, pods, and seeds because the flowering period was shortened and some of the flowers were aborted. Korte et al. reported 1) that irrigation during flowering had little effect on ultimate seed yield (1983a) but 2) that increased numbers of pods and seeds per plant resulted from irrigation at flowering (1983b). These increases were offset, however, by decreased seed weight. Irrigation during pod elongation increased the number of pods per plant, seeds per plant, and seed weight, resulting in increased seed yield (Korte et al., 1983b). Irrigation during seed enlargement greatly increased seed weight, resulting in large seed yield increases. On the other hand, seed quality was reduced by irrigation.

Models of soybean phenology include air temperature and photo-period (Hodges and French, 1985; Sinclair et al., 1991; Jones et al., 1991). Generally, as air temperature rises, the rate of development increases; therefore, higher air temperature results in shorter durations of various stages, such as seed fill. The low and high night air temperatures that limit seed growth rate are 10°C (Seddigh and Jolliff, 1984b) and 28°C (Egli and Wardlaw, 1980). Beyond these temperatures(<10°C and >28°C) seed growth rate is reduced. For flower fertilization and pod set, the biological minimum temperature for most U.S. cultivars is 15°C (Hume and Jackson, 1981). During the Midwest growing season, continuous temperatures below 15°C are possible only in the extreme northern regions. Night temperatures above 15°C throughout the growing season lead to larger seeds than do temperatures of 10°C. More seeds per pod are produced with night temperatures of 24°C than at cooler temperatures (Seddigh and Jolliff, 1984a).

In an outdoor growth chamber, individual seed weight decreased with higher temperatures, while seed number increased. Temperatures ranged from 26°C day and 10°C night to 36°C day and 29°C at night (Baker et al., 1989). Higher nighttime temperatures (24°C) enhanced early vegetative growth, advanced reproductive development and physiological maturity, and increased seed yield (Seddigh and Jolliff, 1984b). However, final vegetative dry matter, pod weight, and leaf area were generally reduced as night temperatures rose above 10°C. On the other hand, low night temperatures of 10°C restricted seed growth rate, which in turn favored partitioning of the photosynthates to vegetative organs and pod walls.

The effects of low night temperatures on soybean pod set were not off set by high daytime temperatures (Lawn and Hume, 1985). Cool night temperatures of 5 to 7°C resulted in a 100 percent reduction of the plants' photosynthetic capacity the following day (Purcell et al., 1987). The reduced plant photosynthetic capacity continued until the day following one night of recovery at 19°C.

Rationale for the Study

The short-term water stresses used in the above studies would not normally occur in a production setting. The statistical modeling studies relied on spatially and temporally averaged data to evaluate weather effects on crop yields, and did not represent any given location. Consequently, neither type of study lends itself to evaluating corn and soybean yield response to the various rainfall patterns and moisture levels that occur in nature at a given site.

Therefore, as part of a larger study to determine the response of corn and soybeans to rainfall increases due to precipitation augmentation, an experiment was established in mobile rain shelters where typical dry, average, and wet summers were simulated. The typical summer rainfall was approximated by keeping natural rainfall away from the plots and by applying rainfall in amounts typical of the summers. The objective of the experiment was to determine the yield changes that could be expected by increasing the volume of each rainfall event by 25 percent. Rainfall treatments and production practices were constant over the five years of the study from 1987 through 1991. Measurements were taken of the response of various yield components to precipitation augmentation, and increases were related to the yield components to determine the growth period when the crops were affected.

A simultaneous field experiment was conducted in shelters open to natural rainfall. After each rain, one of ten different rainfall additions or treatments was applied. These treatments represented a wide range of possible rain changes that might be produced through cloud seeding. In this experiment, corn and soybean yields were compared to assess the value of the ten individual treatments on annual and five-year bases.

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METHODS AND PROCEDURES

Three different but related experiments were conducted during the summers of 1987 through 1991. In one experiment, called the "mobile shelter study," corn and soybeans were planted so that mobile rain shelters could be moved over them to exclude all natural rainfall. The mobile rain shelters were equipped with sprinklers that allowed the application of prescribed quantities of water to each plot at specified times. The goal was to apply the same amount of water during the same growth stages each year. Six water treatments were designed to represent typical dry, average, and wet summers in east-central Illinois, plus standard rainfall additions.

In the second experiment, a "planting date and population" study, corn was planted under two shelters with two different planting dates and two different plant densities each year. Water applications were the same as for the mobile shelter study.

In the third experiment, corn and soybeans were planted in an open area equipped with a sprinkler irrigation system. The "open-area study" involved additions of ten different quantities of water to natural rainfall events, based on the amount of rain received. The additional water was applied using a sprinkler system the day following the natural rains.

Mobile Shelter Rainfall Models

Rain treatments in the shelters approximated typical dry, average, and wet summer rains, to which was added 25 percent more water. The 25 percent increase was selected to simulate the effects of rainfall increases due to cloud seeding.

A long, 85-year, high-quality historical data set was used to select the dates of rain and no rain, the daily amounts of rain, the time of day of the rain, and the rain rates for typical dry, average, and wet summers. A variety of models can generate daily rainfall sequences. Most features of daily rainfall are highly sensitive to the model chosen. Buishard (1978) recommended that the process chosen should fit the available database and the application desired. After considering various processes and applications for this study, a climatological frequency method, rather than a Markov chain or other complex statistical process, was chosen to determine the distribution of wet and dry days and the amounts of rain on wet days.

Definition of each summer rain type began by developing monthly rainfall totals for June, July, and August These totals helped identify "target" rainfall amounts for typical dry, average, and wet summers. The three values were defined using the average of the 17 driest summers of the 85-year record to represent the "dry summer," the average of the 17 summers with rain nearest the 85-year average as the "average summer," and the average of the 17 wettest summers as the "wet summer."

Monthly rainfall totals were then used as "targets" for the sum of the daily rain values. The detailed daily analysis was completed for the near-average summer conditions first. Then the dry and wet summer daily values were developed.

The dry and wet summer rain dates were compared to those established for the near-average summer conditions. This was necessary to achieve comparable crop effects between wet and average, dry and wet, and dry and average summers when the timing of the rain is critical. Historical rain-day data from 1901 through 1985 were used to define the frequency distributions of daily rainfall amounts, and then to distribute these amounts over the 92 days of summer. Finally, climatic information on the time of day of rain was used to develop the diurnal rainfall distributions. All of these data were used to "construct" the three summer rain scenarios.

Daily Rainfall Levels

Frequency distributions of rainy days were determined for each type of summer by analysis of all the months in the 1901-1985 record. There were 2,205 days (28.2 percent of the total days) with measurable rain of at least 0.25 millimeter (mm). The average frequencies of six quantities of rain during the three types of summers (table 1) were obtained by fitting the daily rain amounts with the gamma distribution and selecting the probability of exceeding that rainfall amount.

Inspection of the monthly frequency distributions indicated that increments of 2.5 mm of daily rainfall were a good basis for calculating the individual daily amounts up to 25.4 mm for "average" summer conditions. The average summer had 26 days with ≥ 0.25 mm, and 10 days with rainfall between 0.25 to 2.5 mm. Rainfall of 0.25 to 2.5 mm was divided into ten increments of 0.3, 0.5, 0.8, 1.0, 1.3, 1.5, 1.8, 2.0, 2.3, and 2.5 mm, for a total of 14.0 mm. The rainfall amounts were determined from the historical frequencies of rainfall in the category.

These ten rainfall values were then distributed among the three months according to the monthly frequencies of rain days in this range. Thus, four rain days were assigned to June, three to July, and three to August (table 1). The ten amounts were distributed among the months according to the magnitudes of the average monthly rainfall. June average rainfall is 101.6 mm (table 2), which is 36 percent of the average summer total of 279.7 mm. July average rainfall is 86.8 mm (31 percent of the total), and August average rainfall is 91.3 mm (33 percent of the total). The sum of these ten daily values (14.0 mm) was multiplied by the June percentage (36 percent), resulting in 5.0 mm as a target for the total June rainfall in the 0.25- to 2.5-mm category. Four values were selected from the ten available and combined for a total of 5.6 mm. Those selected for June were 0.5, 0.8, 1.8, and 2.5 mm. This process was repeated for July and August. The daily values totaled 3.9 mm in July and 5.8 mm in August.

Table 1. Average Number of Rain Days for Urbana in the Typical Dry, Near-Average, and Wet Summers

Month	*Days with measurable amounts, ≥ 0.25 mm* Dry	Average	Wet	*Days with 0.25-2.5 mm* Dry	Average	Wet	*Days with 2.6-7.5 mm* Dry	Average	Wet
June	10	10	12	4	4	4	3	3	4
July	7	8	10	3	3	3	2	2	3
August	7	8	10	3	3	2	2	2	4
Total	24	26	32	10	10	9	7	7	11

	Days with 7.6-12.5 mm Dry	Average	Wet	*Days with 12.6-25.4 mm* Dry	Average	Wet	*Days with >25.4 mm* Dry	Average	Wet
June	1	1	1	1	1	1	1	1	2
July	1	1	1	1	1	1	0	1	2
August	1	1	1	1	1	1	0	1	2
Total	3	3	3	3	3	3	1	3	6

This process of partitioning daily rainfall values by months was repeated for those values in all the other 2.5-mm rain intervals above 2.5 mm. Four rain days amounted to 2.6 to 5.0 mm per day in the average summer (two in June, one in July, and one in August). Three rain days (one in each month) ranged from 5.1 to 7.5 mm. Their combined values, 2.6 to 7.5 mm, are shown in table 1. Frequency analysis of the historical values in each class was again used to determine the values selected: 3.1 and 3.9 mm for the 2.6- to 5.0-range, and 6.4 mm for the 5.1- to 7.5-category.

As shown in table 1, the categories of 7.6 to 12.5, 12.6 to 25.4, and >25.4 mm averaged three rain days each in the average summer. The rain-day values from 7.6 to 25.4 mm were selected based on the frequency distributions for the levels of 7.6 to 12.5 and 12.6 to 25.4 mm. They were partitioned among months according to how well they approximated the average monthly totals. The June values selected for the average summer (table 2) were 15.5 and 17.8 mm; the July values were 8.9 and 22.9 mm; and those for August were 12.4 and 21.6 mm.

The final rain days to be assigned were those measuring >25.4 mm. The 2.5-mm increment frequency analysis was stopped at this level because of the rarity of rain days with rainfall >25.4 mm. As shown in table 1, the average summer saw one such day each month. The rain magnitude for each day was established by summing all the other daily values already assigned, and then subtracting this total from the monthly average total. For example, in June the rain on nine rain days with <25.4 mm totaled 58.2 mm. These heavy rain days can be identified in table 2 as those days with total rainfall >25.4 mm, or 39.9 mm in July and 42.9 mm in August.

Temporal Distribution of Rain Days

The summer rain days then had to be assigned to each month. Analysis showed that 54 percent of all summer rain days in Urbana occurred in pairs, but only 2 percent occurred on three successive days. Therefore, six of the ten rain days in the average June were used to form three pairs of rain days. Two pairs were used in July and two pairs in August Because 67 percent of the historical two-day sequences included one day with more than ten times the rain of the other day, five of the seven pairs of rain days in the average summer included one value that was more than ten times greater than the other. Analysis further revealed that in 64 percent of the cases, the first-day value of the pair was less than the second day's. Hence, in five of the seven pairs, the first day's rain was less than one-tenth of the second day's rain. The first day of the remaining pairs had more than ten times the rain of the second day of the pair.

Additional data to establish the temporal distributions of rain days throughout each month were obtained from calculations of the average daily rainfall per day and from studies of the probabilities of dry and wet days for one- to seven-day durations for Urbana (Feyerherm et al., 1966), based on the Markov chain probability model. These data identified parts of each month apt to fall in wet periods (>0.25 mm of rain per day). Initially, the mean daily rainfall was calculated for each date from 1901 through 1985. These calculations revealed certain periods that had proportionately higher (and lower) values than those expected (~3.3 percent per day). The probabilities that the dates selected would be wet were at least 10 percent higher than on other summer days.

The five wet periods, including their historical percentages of monthly total rainfall and the expected totals, are listed in table A1. The rain days and amounts assigned to each month were concentrated in these wet periods. The daily amounts already assigned to each month were selected to produce totals that approximated the total rain in each wet period. These rain-day values are listed in table 2, and the resulting totals, expressed as a percentage of the monthly totals, appear in table A1. The number of rain days in each wet period was set to

Table 2. Modeled Summer Daily Rainfall Values for Urbana in Typical Dry, Average and Wet Summer Conditions (mm)

	June			*July*			*August*		
Month	*Dry*	*Average*	*Wet*	*Dry*	*Average*	*Wet*	*Dry*	*Average*	*Wet*
1									
2						0.5	1.3	1.3	6.4
3	6.9	7.1	9.1				9.1	21.6	24.1
4	2.8	2.8	2.8	0.5	1.3	1.3			
5				20.3	39.9	46.7			
6									
7									
8	10.4	17.8	19.1						
9				2.0	8.9	10.2			
10	0.8	0.8	0.8			5.1	2.3	3.3	5.1
11									
12									
13							2.5	2.5	4.8
14	28.4	43.4	45.7		2.3	6.1	19.1	42.9	43.2
15	0.5	0.5	0.5						
16									
17									
18							5.1	12.4	12.4
19	4.3	9.4	9.4						0.3
20									
21				0.3	0.3	2.3			
22				10.6	22.9	39.4			
23	12.7	15.5	16.5						
24							2.0	2.0	2.0
25									52.3
26	2.5	2.5	26.9						
27	1.8	1.8	2.5	2.8	4.8	5.3			
28							4.3	5.3	5.3
29			0.3						
30			6.1	6.4	6.4	10.2			

exceed the expected frequency if the days had been evenly distributed throughout the month.

The final assignment of the rain days to actual days in each month was controlled by the selection of the seven pairs of rain days previously described and by the amounts (and days) selected to be in the five wet periods. The distribution of the number of dry days between wet days from 1901 through 1985 was calculated and used to assign the rain days.

This analysis showed that 22 percent of the rain days occurred on two consecutive days; 8 percent were one day apart; 18 percent were two days apart; 27 percent were three days; 14 percent were four days; 6 percent were five days; 3 percent were six days; and 2 percent were seven days or more apart. These percentages were used to distribute the rain days during the average summer.

The result was seven rain-day pairs, one with one dry day between them, five with two dry days between rains, eight with three dry days, and two periods each with four, five, and six dry days between rains. This array closely approximated the historical 85-year distribution.

A coin toss (between five and six days between rains, and the sequences of two and three dry days) was used to establish the first rain day in June (table 2). Thereafter, dry-day periods were assigned through 31 August by selecting numbered slips of paper so that the frequency of numbers matched the established rain-day frequency (one slip with one dry day, five slips with two dry days, etc.). The actual rain-day amounts (and pairs) were also listed on the individual slips and drawn to distribute the rain amounts to the rain days. This process confirmed the previous choices of rain-day pairs and the assignment of rain days to the wet periods. The resulting distribution of rain days for the average summer in Urbana, and the rain distributions constructed for the typical dry and wet summers are shown in table 2.

The rain-day values for the typical dry and wet summers were based on several criteria and were determined in a manner similar to that used for the average summer. First, the dry and wet summer monthly rainfall totals were used as targets for the sum of the daily values. These monthly values for the typical dry and wet June, July, and August appear in table 2.

In order to compare crop yields in response to the dry, average, and wet summer rainfall treatments, the rain-day distributions established for the average summer were used for the dry and wet summer conditions. Therefore, the daily rain magnitudes differed for the dry and wet summer conditions, but not the rain dates. However, as noted below, the number of rain days was altered to fit the historical averages of the wet and dry rain-day frequencies.

The averages of the rain-day frequencies at the levels shown in table 1 were followed. The process used in the dry July illustrates the procedure followed for each dry month. In a typical dry summer, July has seven days with rainfall >0.25 mm, one less than the average summer. This means that for a dry July, one rain day had to be deleted from those selected for the average July. A day with a relatively low value, such as 2.3 mm of rainfall on 14 July in an average summer, was selected for deletion, as was one day in August.

The historical rain-day frequencies for the 17 dry summers were used to identify distributions for each of the 2.5-mm intervals from 0.25 to 25.4 mm. These values were then arrayed against the daily amounts of average summer rains (table 2) to ensure that the value assigned to each date was equal to or less than the value in the average summer.

In a similar fashion, the daily values in the wet summers were constructed and arrayed against the dates of rain for the average summer. The guiding criteria ensured that the readjusted values met the monthly averages for the wet summer rain-day frequencies (table 1), and that their totals matched the monthly totals in table 2. Historical wet summer daily rainfall distributions were used to select the values in the 2.5-mm intervals. These values were assigned to the dates of the average summer rain days, so that their totals equaled or exceeded the average summer values.

The six additional rain days in the wet summer were assigned according to the monthly average frequencies: two in June, two in July, and two in August. The criteria used for these six days matched the historical single and paired rain-day frequencies, with about 54 percent paired. Hence, five of these added rain days were used to form pairs, and the remaining day was left as a single event. They also were not assigned to the five wet periods (table A1) because the assigned rain values already exceeded the historical values.

The dry-day spacing was further limited to one or two days between the new and already existing rain days. With these criteria, candidate dates for each month (such as 1, 17 June, etc.) were entered on slips of paper, and the two dates were blindly selected. The dates selected for the two added days were 29 and 30 June, forming a pair. Other rain-day pairs were created with 10 July, 20 August, and 25 August. The additional single rain day in July was selected by the same process.

In-Day Rain Distribution

Once daily rainfall amounts were assigned to dates, the time of the rain event in each day was determined. The historical 85-year data did not include hourly values from which to derive diurnal distributions for the dry, average, and wet summers. However, the average diurnal distribution of summer rainfall in the Urbana area, which is based on 20 years of data (Huff, 1971), was used to establish general diurnal distributions. The results show that the period of 0900 to 1300 local standard time (LST) is a low-incidence period, and each hour receives an average of 3 percent of the day's rain. Between 1300 and 2000 LST, each hour receives about 4 percent of the rain; and between 2000 and 0900 LST, each hour receives about 5 percent of the total rain. This distribution reflects a nocturnal maximum and a midday minimum; 62 percent of the summer rain falls in the 13 hours from 2000 to 0900 LST, 26 percent from 1300 to 2000 LST, and 12 percent from 0900 to 1300 LST.

These percentages were used to distribute the rain events in a repeated six-day sequence of rain days from 1 June through 31 August. The sequence approximated the average diurnal distribution: three events at night (2000-0900 LST), two in the afternoon (1300-2000 LST), and one in the morning (0900-1300 LST). The order was determined by putting each option on one of six slips of paper, which were selected by a blind draw.

The sequence drawn was afternoon, night, afternoon, night, night, and morning. The starting hours selected for afternoon and night rain periods were varied: beginning with the first rain day (3 June) the rain began at 1300 LST. On the second day, rain began at 0500 LST. On the third rain day in the sequence, the afternoon rain was set to begin at 1600 LST. On the fourth day rain began at 2000 LST, and on the fifth day at 0100 LST. On the sixth day, rain began at 0900 LST. With 26 rain days in the average summer, the sequence of six days was repeated four times, with the last two days beginning at 1300 and 0500 LST.

Rain treatments in the mobile shelters were thus designed to simulate typical dry, average, and wet summers. Then 25 percent more water was added to each of the three original simulations to approximate the effects of rainfall increases that might be generated by cloud seeding. Thus, six different rainfall treatments were applied to the plots in the mobile shelter experiments:

1. Rainfall typical of a dry summer.
2. Rainfall typical of a dry summer, plus 25 percent.
3. Rainfall typical for an average summer.
4. Rainfall typical of an average summer, plus 25 percent.
5. Rainfall typical for a wet summer.
6. Rainfall typical of a wet summer, plus 25 percent.

Open-Area Rainfall Models

The water treatments added to rain events were based on evidence of modified rain from summer-season convective clouds. The St. Louis and Chicago studies of inadvertent rain changes (Changnon et al., 1981; Changnon, 1980) showed 1) 10 to 25 percent average areal increases in summer rainfall; and 2) that the rain events most commonly enhanced were those that occurred during moderate regional rainfall (2.5 to 25.4 mm) or heavy rainfall (>25.4 mm per day). Assessment of rain changes in five Illinois cloud seeding experiments, although far from statistically significant, suggested summer rain increases of 4 to 37 percent in three projects with no increases in two projects (Changnon and Hsu, 1981). Experiments with summer convective clouds in the High Plains revealed increases ranging from 2 to 61 percent (Dennis, 1980).

Collectively, these and other modification projects suggest that rainfall increases of about 10 to 40 percent above the naturally occurring summer rainfall might be produced in Illinois under certain rain conditions (Weather Modification Board, 1978). Thus, water increases for this experiment were set to include 10, 25, and 40 percent of the actual rainfall. Results for individual rain days also suggested the success of weather modification in certain conditions when daily rainfall is relatively light (<2.5 mm), moderate (2.5 to 25.4 mm), and heavy (>25.4 mm). The number of available open plots limited the experiment to ten treatments that were selected from the above parameters. The ten treatments included the naturally occurring rainfall as a control (1). Three treatments were increases of 10, 25, and 40 percent applied to all rains that occurred during the summer (2,3,4). Other treatments included increases only to **light rains** of ≤2.54 mm (10)**;** to **moderate rains** of 2.54 to 25.4 mm (5, 6, 7); and to **heavy rains** of ≥ 25.4 mm (8, 9). The range of treatments and levels of rain events chosen were considered sufficient to bracket most outcomes for purposeful rainfall modification, both as to the magnitude of the rain increase attainable and to the rainfall conditions during which increases might occur or be agriculturally desirable in Illinois. Following are the ten rainfall treatments applied to the open-area plots:

1. Natural rainfall.
2. Increase all daily rains 10 percent.
3. Increase all daily rains 25 percent.
4. Increase all daily rains 40 percent.
5. Increase all daily rains of 2.54 mm to 25.4 mm by 10 percent (moderate rain).
6. Increase all daily rains of 2.54 mm to 25.4 mm by 25 percent (moderate rain).
7. Increase all daily rains of 2.54 mm to 25.4 mm by 40 percent (moderate rain).
8. Increase all daily rains above 25.4 mm by 10 percent (heavy rain).
9. Increase all daily rains above 25.4 mm by 40 percent (heavy rain).
10. Increase all daily rains less than 2.54 mm by 40 percent (light rain).

Mobile Shelter Corn and Soybean Experiments

Corn and soybean growth experiments were conducted under mobile shelters from 1987 through 1991. Investigation of the response of corn and soybeans to typical dry, average, and wet summer rain regimes required a special facility where natural rainfall could be excluded from the plots and prescribed amounts of water could be applied following the rainfall models described above. The University of Illinois at Urbana-Champaign possessed a facility that met these requirements at its South Farms (Banwart, 1987, 1988).

The field facility (figure 1) consisted of four aluminum frame shelters covered with plastic. Each shelter was mounted

Figure 1. Overview of the mobile rain shelters and the open-area plots used in the experiments

on a track and equipped with electric motors and rain sensors. When rain was detected by the sensor, the motors moved the shelters over the plots. After the rain stopped and the sensor dried off, the motors moved the shelters off the plots. Therefore, the shelters covered the crop only during rainy periods or when water treatments were being applied. Each shelter covered 36 plots, 3 by 3 meters (m) each, for a total covered area of 10 by 39 m (33 by 128 ft). The plots were arranged in three north-south rows with 12 plots per row.

The six simulated rainfall treatments described above, typical of dry, average, and wet summers, plus 25 percent to each, were applied to the corn and soybeans in one shelter each year. Each treatment was replicated three times on both corn and soybeans in each shelter. The six treatments were arranged in each of the three rows in a randomized complete-block design. Although the 1987 and 1988 studies were conducted in different shelters, they used the same randomization scheme (figure 2). A new randomization scheme was developed in 1989 for the last three years of the study, all of which were conducted in the same shelter as the 1988 study.

The soil in the shelters was a Drummer silty-clay-loam (fine-silty, mixed, mesic Typic Haplaquolls), which is a typical agricultural soil of east-central Illinois. Because the Drummer soil is naturally poorly drained, drainage tile was installed one meter below the soil surface in the plot area. Therefore soil in the plots could be classified as moderately well drained.

1987-1988 Treatments				1989-1991 Treatments		
18 Corn W	12 Corn A + 25%	6 Cora A + 25%		18 Corn W	12 Cora D	6 Corn A + 25%
17 Corn A + 25%	11 Corn W + 25%	5 Cora A		17 Cora D	11 Corn W	5 Corn W
16 Corn A	10 Corn W	4 Cora W		16 Cora A + 25%	10 Corn W + 25%	4 Corn W + 25%
15 Corn D	9 Corn D	3 Corn D + 25%		15 Corn W + 25%	9 Corn A + 25%	3 Corn A
14 Corn D + 25%	8 Corn A	2 Cora W + 25%		14 Cora A	8 Corn D + 25%	2 Corn D + 25%
13 Corn W + 25%	7 Corn D + 25%	1 Cora D		13 Corn D + 25%	7 Corn A	1 Cora D
36 Soy W + 25%	30 Soy D	24 Soy A + 25%		36 Soy A + 25%	30 Soy W	24 Soy W + 25%
35 Soy A	29 Soy W	23 Soy W		35 Soy W + 25%	29 Soy D	23 Soy A
34 Soy W	28 Soy W + 25%	22 Soy D + 25%		34 Soy W	28 Soy A	22 Soy D
33 Soy D	27 Soy A + 25%	21 Soy W + 25%		33 Soy D	27 Soy W + 25%	21 Soy D + 25%
32 Soy A + 25%	26 Soy A	20 Soy A		32 Soy A	26 Soy D + 25%	20 Soy A + 25%
31 Soy D + 25%	25 Soy D + 25%	19 Soy D		31 Soy D + 25%	25 Soy A + 25%	19 Soy W

Notes: (D = typical dry year; A = typical average year; W = typical wet year).

Figure 2. Plot layout and water treatment randomization for corn and soybeans in the mobile shelters

Organic matter throughout the soil surface was high (4 to 5 percent), with a relatively high water-holding capacity at 2.2 mm per centimeter (cm).

The 1987 mobile shelter study plots were planted on 28 May using a B73 x Mo17 corn hybrid and Williams soybean variety. Plant populations were 81,500 corn plants/ha and 353,000 soybeans plants/ha. The corn plots were fertilized with 224 kilograms (kg) of nitrogen (N) per hectare, 56 kg/ha of phosphorus (P), and 223 kg/ha of potassium (K). P and K were applied to the soybean plots at rates of 56 kg/ha, and 223 kg/ha, respectively. All the fertilizers were applied before planting and incorporated into the soil with the last tillage operation.

The 1988 corn and soybean crops were planted on 12May. The corn population was 64,000 plants/ha, and the soybean population was 230,000 plants/ha. All plots were fertilized as they were in 1987, and the same corn hybrid and soybean variety were used. However, the corn plots were treated with 4.9 liter (L) of Sutan per ha, 455 grams (g) per hectare of Atrazine; and 455 g/ha of Bladex incorporated into the soil before planting. The soybean plots were treated with 4.9 L/ha of Treflan. On 13 July, the soybeans received Cygon garden spray at the rate of 2.5 L/ha to control spider mites.

The mobile shelter experiment conducted in 1987-1988 was repeated in 1988-1991. Corn and soybeans were planted on 13 May 1989 with the same populations used in 1988. The corn hybrid and the soybean variety were the same used in 1987 and 1988. All the corn plots were fertilized before planting with 224 kg/ha of N, 56 kg/ha of P, and 168 kg/ha of K. Each of the soybean plots was fertilized with 56 kg/ha of P and 168 kg/ha of K before planting. The corn plots were treated with Bladex at 910 g/ha and Atrazine at 455 g/ha to control weeds. Treflan was applied to the soybean plots at 4.9 L/ha to control weeds. All the herbicides were applied pre¬emergence.

The mobile shelter experiment was repeated in 1990, and planting took place on 30 May. All the procedures and the randomization scheme, as well as all the fertilizers and weed control treatments, were the exactly the same as those used in the previous year, 1989.

The final year of the mobile shelter experiment was 1991. Corn and soybeans were planted on 16 May. A more modern corn hybrid (Pioneer 3379) was substituted for the B73 x Mo 17 hybrid, but the soybean variety was unchanged. Fertilizers were applied to both crops at the same rates as in previous year. The soybeans were treated with the same herbicides as before, but the corn was not treated in 1991.

Planting Date and Population Study

Because different planting dates and corn plant populations were used in 1987 and 1988, a planting date and plant population study was conducted during the summers of 1989, 1990, and 1991.

In 1989, corn was planted on 13 and 31 May in shelters 3 and 4. The desired plant populations were obtained by overseeding the corn on each planting date and then thinning to populations of 64,000 and 82,500 plants/ha. Both planting dates were applied as block treatments, although plant populations and water treatments were randomized within the groups planted on the same dates. Two rain shelters were used, so that each planting date and population combination (figure 3) was repeated three times. The same fertilizers and weed controls applied to the regular mobile shelter plots were applied to these.

The same procedures and randomization scheme were used in 1990. Plantings occurred on 24 May and 5 June. All the fertilizer and weed control treatments on the corn and soybean plots were the same as in 1989.

The final year of the plan ting date and population study was 1991. The early planting date was 16 May and the late date was 30 May. The more modern corn hybrid, Pioneer 3379, was substituted for the B73 x Mo17, just as in the regular mobile shelter corn plot All the corn plots were treated with the same herbicides and rates as in previous years.

Open-Area Corn and Soybean Studies

The open-area corn and soybean experiments were also conducted from 1987 through 1991. In 1991, only corn was planted in the open-area study. All ten water treatments were applied to the corn and soybeans in June, July, and August 1987 through 1990. Only treatments 1 through 4 were applied to the corn in 1991. The randomization scheme of the ten treatments is presented in figure 4. Corn and soybeans were planted on 28 May 1987 using a B73 x Mo17 corn hybrid and a Williams soybean variety. The corn crop was planted at a density of 81, 500 plants/ha, and the soybeans at 353,000 plants/ha. Fertilizers were applied preplant to the corn plots at an elemental N rate of 341 kg/ha, 94 kg/ha of P and 94 kg/ha of K. The soybean plots were fertilized with 94 kg/ha of P and 94 kg/ha of K. Herbicides were not applied to the plots in 1987,butweeds were controlled by hand cultivation.

In 1988, corn and soybeans in the open-area study were planted 12 May. In 1989 soybeans were planted on 12 May and corn on 13 May. In 1990 corn was planted on 24 May and soybeans on 30 May. Corn was planted 15 May in 1991. Corn plant density was 64,000 plants/ha for all the plantings for 1988 through 1991. The soybean plant density for 1988 through 1990 was 230,000 plants/ha. The soybean portion of this experiment was terminated after 1990.

Fertilizer was applied to the corn plots before planting. In 1988 K was applied at 112 kg/ha, and in 1989 through 1991 it was applied at 168 kg/ha. From 1988 through 1991, the plots

Shelter # 3				Shelter # 4		
318 A + 25% E L_d	312 D E L_d	306 D + 25% E H_d		418 A + 25% E H_d	412 A E L_d	406 D E L_d
317 W + 25% E L_d	311 D E H_d	305 A E L_d		417 W + 25% E H_d	411 A E H_d	405 W + 25% E L_d
316 W + 25% E L_d	310 A + 25% E H_d	304 W + 25% E H_d		416 A E L_d	410 D + 25% E L_d	404W E H_d
315 W + 25% E L_d	309 D + 25% E L_d	303 D E H_d		415 W E L_d	409 D + 25% E H_d	403 W E L_d
314 A E H_d	308 W E H_d	302D E L_d		414 D + 25% E H_d	408 A + 25% E H_d	402 D + 25% E L_d
313 W E L_d	307A E H_d	301 A + 25% E L_d		413 A + 25% E L_d	407 W E H_d	401 D E H_d
336 D L L_d	330 D L H_d	324 A + 25% L L_d		436 D L L_d	430 A L H_d	424 W + 25% L H_d
335 D + 25% L L_d	329 A + 25% L H_d	323 W L L_d		435 W + 25% L L_d	429 W + 25% L H_d	423 W L L_d
334 A L L_d	328 W + 25% L L_d	322 W L H_d		434 D + 25% L H_d	428 W L H_d	422 W + 25% L L_d
333 D + 25% L L_d	327 A L L_d	321 W + 25% L L_d		433 D + 25% L L_d	427 D L L_d	421 D + 25% L L_d
332 W L H_d	326 A + 25% L H_d	320 W L L_d		432 D L H_d	426 A + 25% L L_d	420 A L H_d
331 D L H_d	325 A + 25% L L_d	319 A L H_d		431 D + 25% L H_d	425 A L L_d	419 A + 25% L H_d

Notes: D = typical dry year, A = typical average year, and W = typical wet year, and E = early planting date. L = late planting date, L_d = low-density population, and H_d = high-density population.

Figure 3. Water treatments, planting dates, and population randomization used in the planting date and population study

received 225 kg/ha of N and 56 kg/ha of P. The soybean plots were also fertilized before planting. They received 56 kg/ha of P in 1988 through 1990, 112 kg/ha of K in 1988, and 168 kg/ha of Kin 1989 and 1990.

Pre-emergence herbicides were applied to the plots beginning in 1988. The corn plots received4.7 L/ha of Sutan, 5.4 kg/ha of Atrazine, and 5.4 kg/ha of Bladex in 1988; and 2.2 kg/ha of Dual and 1.1 kg/ha of Atrazine in 1989 through 1991. The soybean plots received 2.3 L/ha of Treflan each summer, 1988 through 1990.

Corn Harvest Procedure

At harvest, 2.44 m of the two center rows of the four rows in each corn plot were harvested to measure yield. The harvested plants were counted and the number of barren plants recorded. Barren plants were defined as those without any ears or with ears without kernels. The ears from each plant were removed and the number of rows on each ear and the number of kernels per row were determined. Ears without well-defined rows were classified as "nubbins." The kernels on the nubbins were counted, and the number of rows recorded as "0."

In 1987, the kernels on each ear were counted, and the number of kernels per row was then determined by dividing the total number of kernels by the number of rows per ear. The grain from the two harvested rows was combined to determine yield in 1987.

In 1988-1991, the number of kernels per row was determined by counting the kernels in an average row on each ear. The number of kernels per ear was computed from the number of rows per ear and the number of kernels per average row. After the kernels had been shelled from the ears, all the grain from each plant within the harvest row was combined to obtain the yield for each harvest row.

Open-Area Soybean

160 Treat 1	150 Treat 7	140 Treat 6
159 Treat 3	149 Treat 7	139 Treat 4
158 Treat 10	148 Treat 4	138 Treat 3
157 Treat 5	147 Treat 2	137 Treat 5
156 Treat 3	146 Treat 6	136 Treat 1
155 Treat 10	145 Treat 7	135 Treat 6
154 Treat 9	144 Treat 2	134 Treat 8
153 Treat 1	143 Treat 9	133 Treat 10
152 Treat 2	142 Treat 4	132 Treat 9
151 Treat 5	141 Treat 8	131 Treat 8

Open-Area Corn

130 Treat 1	120 Treat 4	110 Treat 1
129 Treat 9	119 Treat 5	109 Treat 8
128 Treat 1	118 Treat 3	108 Treat 7
127 Treat 3	117 Treat 7	107 Treat 9
126 Treat 2	116 Treat 2	106 Treat 10
125 Treat 9	115 Treat 5	105 Treat 5
124 Treat 3	114 Treat 2	104 Treat 7
123 Treat 4	113 Treat 10	103 Treat 4
122 Treat 6	112 Treat 6	102 Treat 10
121 Treat 8	111 Treat 6	101 Treat 8

Treatment 1 = Natural rainfall.
Treatment 2 = Increase all daily rains 10%.
Treatment 3 = Increase all daily rains 25%.
Treatment 4 = Increase all daily rains 40%.
Treatment 5 = Increase all daily rains of 2.54 mm to 25.4 mm by 10%.
Treatment 6 = Increase all daily rains of 2.54 mm to 25.4 mm by 25%.
Treatment 7 = Increase all daily rains of 2.54 mm to 25.4 mm by 40%.
Treatment 8 = Increase all daily rains Above 25.4 mm by 10%.
Treatment 9 = Increase all daily rains Above 25.4 mm by 40%.
Treatment 10 = Increase all daily rains Less than 234 mm by 40%.

Figure 4. Corn and soybean water treatments and randomization patterns in the open-area experiment

Moisture content of the grain was measured using a Dickey John grain moisture tester. The dry weight of the cobs and the stover, the leaves and stem of the plant, were determined after being oven-dried for 24 hours at 60°C.

Kernel mass was determined in 1987 by dividing the kernel mass from each ear by the number of kernels on that ear. In 1988 and 1989 the kernel mass was estimated by dividing the total grain yield of the harvest row by the number of kernels in that harvest row. The mass of 200 kernels was determined from a random sample from each harvest row in 1990 and 1991.

Soybean Harvest Procedure

The center 2.44 m of the two middle rows of each soybean plot were harvested to determine soybean yield. When harvested, a 0.61-m section of the row was randomly selected, and the number of plants and the number of pods with or without beans on each plant in that section were counted to determine the yield components for each harvest row. To determine row yield, the plants from the remaining 1.83 m of plot row were harvested, the pods shelled, and the beans were combined with those from the 0.61-m row section. The pod shells were combined with the harvested soybean plant parts, dried, and weighed to determine the vegetative dry weight.

Weather Data Analysis

Air temperature data were obtained from a weather station 1 km west of the plots. Rainfall during the growing season was measured at the plots. When the crop was not growing, rainfall was measured at the weather station west of the plots.

The start and stop of each corn growth stage was determined by computing the growing degree accumulation required to reach each of the different stages (Hollinger, 1981). Six corn growth stages were identified:

1. Planting to tassel initiation
2. Tassel initiation to ear initiation
3. Ear initiation to end of row set
4. End of row set to silk
5. Silk to end of lag phase
6. End of lag phase to maturity.

Average maximum and minimum temperatures were computed for each of the growth stages using the daily maximum and minimum temperature data from the weather station.

The soybean growth stages were simulated using the model of Jones et al. (1991) contained in the SOYGRO Model (Wilkerson et al., 1983). Four soybean growth stages were identified:

1. Planting to first unifoliate
2. First unifoliate to floral induction
3. Floral induction to first flower
4. First flower to maturity

ANALYSIS AND RESULTS

The summer weather from 1987 through 1991 and yields in the three experiments varied considerably from year to year. This chapter presents an analysis of the weather during the five-year period of the experiments, the yield results of the various experiments, and the relationships between weather and yields. Included is an analysis of variance of the corn and soybean experiments in the shelters and in the open area, and correlation and regression analyses using the weather conditions during the different crop growth stages as independent variables, and the final yields and yield components as dependent variables.

Weather Conditions, 1987-1991

The five-year sample (1987-1991) of weather conditions during the field experiments is subject to the natural weather conditions before, during, and after the experiment. The most critical rainfall period for corn and soybeans in Illinois has been found to be June through August (Odell, 1959; Huff and Changnon, 1972).From 1987 through 1991, the growing season in this deep prairie soil began with saturated soil moisture, as in 95 percent of all years (Swanson and Smith, 1971). Little significant soil moisture depletion occurs during May.

Temperatures varied widely during the five years of the experiment (table 3), from near record-high summer temperatures in 1988 and 1991, to near average in 1989, to below-average in 1990. Also shown in table 3 are the number of days with maximum temperatures of 32.2°C (90"F) or higher in each year and the average number expected. This maximum temperature reflects days with major corn stress (Herrero and Johnson, 1980).

The lower portion of table 3 presents data on certain precipitation conditions experienced during 1987-1991. Total summer precipitation varied from near average in 1989, to near

Table 3. Monthly Weather Conditions and Climatological Departures, at the Official Champaign Cooperative Weather Station, 1987-1991

Temperature Conditions

	June		*July*		*August*		*Summer*	
	Mean dep[1]	*Days*[3]	*Mean dep*[1]	*Days*[3]	*Mean dep*[1]	*Days*[3]	*Mean dep*[1]	*Days*[3]
1987	+1.5	8	+0.2	9	+0.0	5	+0.6	22
1988	+0.8	16	+1.6	18	+2.1	16	+1.5	50
1989	-0.2	4	+0.0	7	+0.1	3	-0.1	14
1990	+0.1	6	-1.1	4	-0.7	5	-0.6	15
1991	+2.2	11	+0.6	12	+13	11	+1.4	34
Average	22.2	6	24.0	8	22.8	5	23.0	19

Rainfall Conditions

	June		*July*		*August*		*Summer*	
	Total dep[2]	*Days*[4]	*Total dep*[1]	*Days*[4]	*Total dep*[2]	*Days*[4]	*Total dep*[2]	*Days*[4]
1987	+27.2	3	+88.6	1	+34.2	2	+150.0	**6**
1988	-91.5	**0**	-18.0	1	-61.4	0	-170.8	1
1989	+27.9	2	-653	0	+15.5	0	-21.9	2
1990	+112.0	3	-183	1	-30.0	0	+63.7	4
1991	-82.8	**0**	-44.7	1	-353	1	-162.8	2
Average	99.6	1	1105	1	93.0	1	303.1	3

Notes: The Champaign Cooperative Weather Station is located 1 km west of the experimental plots.
[1] Monthly mean temperature expressed as departure from the 1951-1980 average (°C).
[2] Monthly total rainfall expressed as departure from the 1951-1980 average (mm)
[3] Days refers to the number with maximum temperatures ≥ 32.2°C
[4] Days refers to the number with rainfall ≥ 25.4 mm.

record lows in 1988 and 1991. The 1988 rainfall was the second lowest summer total since local records began in 1903. Above-average rainfall occurred in 1990, and much above in 1987. The frequencies of heavy rain days (>25.4 mm) are also shown, since they often greatly affect crop yields.

The summers of 1987 and 1990 presented an interesting contrast, the former being relatively warm and wet, and the latter being relatively cool and wet. Summer 1988 was extremely hot and dry, whereas summer 1989 had average weather conditions. Summer 1991, like 1988, was warm and dry.

The relatively short sample of seasons provided a wide range of summer weather conditions. However, as Aristotle said in the *Nicomachean Ethics,* "One swallow does not a summer make." Nor do five summers represent the spectrum of growing seasons in a humid continental climate. A study of 60 years of summer weather conditions affecting Illinois crop yields identified 17 different growing season types (Changnon, 1969). However, it is not feasible to operate costly field trials for the 30 to 50 years required to obtain an adequate sampling of all the various weather conditions. Furthermore, agricultural practices and yields shift greatly over time (Swanson and Nyankori, 1979), and a long, fixed experiment is not justified. Planting densities, fertilizer applications, and seed varieties of 1990 differ from those employed 10 to 20 years ago.

In this experiment, the crop-weather relations were sampled in one regionally representative soil area for five years, recognizing that the results would have limitations based on the weather experienced. Nevertheless, the results should provide useful guidelines as to the general relationships of added rainfall to corn and soybean yields grown according to current agricultural practices. Study of corn yield-weather-soil relations for Illinois' 102 counties revealed that most of the 53 counties in the northern half of Illinois, which has the state's highest average crop yields, had corn yield losses due to weather that were less than 35 percent of the mean yield (Changnon and Neill, 1967). Hence, their soils and weather conditions are very similar.

The conditions in the five summers sampled during 1987-1991 were compared with those in 17 types of growing seasons identified (Changnon, 1969). Growing-season weather conditions like those in 1988 occurred 8 percent of the time (five summers in 60 years). Conditions like those in 1989 also occurred in 8 percent of those summers, the 1987 type occurred in 6 percent, the 1991 type in 3 percent, and the 1990 type in 4 percent. Thus, the five summer crop-weather types sampled represent 30 percent of the total types of growing seasons in central Illinois.

Rainfall Timing

During the five-year study period, the summer frequency of heavy rain days (>25.4 mm) varied greatly, ranging from a low of one day in 1988 to a high of six days in 1987 (table 3). The average is three days, and the probability for one day or less in a summer is 26 percent, based on 89 years of record. The probability for six or seven heavy rain days is 11 percent, revealing that the heavy rain-day extremes were well sampled during 1987-1991.

Weather and crop yield studies at the farm level (Changnon and Neill, 1968) revealed mat in July and August, rainfall was more critical than in June. Inspection of the sampled July rain totals (table 3) shows that four of the five Julys and three of the five Augusts had below-average rainfall. This situation indicates mat rainfall additions in July and August during 1987-1991 should have enhanced yields, depending on whether the rain days occurred at critical times of crop growth.

The rainfall timing for the five-year sample was analyzed using weekly amounts. Changnon and Neill (1968) analyzed yield data from 60 farms located in a 1,400-km^2 network of 49 weather stations located 40 km west of the experimental plots. Their results showed that weekly rainfall during the weeks of 29 June-5 July, 6-12 July, and 3-9 August was highly correlated with corn yields. The rainfall in these three critical weeks during each of the five summers is presented in table 4.

The different corn yield outcomes for the two hot and dry summers, 1988 and 1991, illustrate the importance of the timing of rain. As shown in table 3, rainfall in both summers was 160 to 170 mm below average, and both mean summer temperatures were 1.4° to 1.5°C above average. The yield differences with natural rainfall were dramatic: 1988 was 6,262 kg/ha, whereas 1991 was 7,581 kg/ha, 21 percent greater than the 1988 yield. The responses to added water treatments also differed greatly: a 48 percent increase in all rains in 1988 brought a yield gain of 2,163 kg/ha (35 percent) whereas the 1991 gain was only 1,007 kg/ha (2 percent).

The yield differences were related largely to the timing of the rains. Note in table 4 that during 1988, essentially no rain fell in the first two critical corn-yield weeks, whereas 1991 received more than 50 mm in two of the three weeks. Moreover, 1991 had fewer hot days, 34 versus 50 in 1988 (table 3). This comparison shows how rainfall increases depend on the timing as well as the amount. In other words, a 40 percent increase to a 30-mm rainfall in late July may be much less important than a 25 percent increase to a 10-mm rain in early July.

The temporal distribution of rain days also varied greatly among the sampled wet summers. Both 1987 and 1990 rated as very wet summers. But table 4 shows that these two summers differed significantly in the amount of rain that fell in the three critical weeks. Rainfall during the three critical weeks in 1987 was moderately heavy in each of the weeks, with above-average rainfall during the week of 29 June-5 July. In 1990, the first two critical weeks had above-normal rainfall and the third week (3-9 August) received very little.

In the hot and dry 1988 summer, the mobile shelter studies tested the effects of 25 percent rainfall increases to corn and soybeans on pre-established dates (Changnon et al., 1989). The plots were covered during all natural rains throughout the summer. Applications of the same total amount of summer

Table 4. Rainfall in Three Critical Weeks and Optimal Values for Corn Production (mm)

	June 29-July 5	*July 6-12*	*August 3-9*
1987	53.3*	23.9	13.4
1988	0.0	1.3	13.5
1989	4.3	0.0	0.8
1990	31.5*	36.8*	4.3
1991	2.6	63.2*	54.6*
Shelter			
Dry	20.8	2.0	9.1
Dry + 25%	26.0*	2.5	11.4
Average	41.2*	8.9	21.6*
Average + 25%	51.5*	11.1	27.0*
Wet	54.9*	15.3	24.1*
Wet + 25%	68.6*	19.1	30.1*
Optimum	76.2	35.6	71.1
Average	23.1	25.0	21.0

Notes: * Value above average.
Rainfall was measured at the official NWS Champaign Cooperative weather station.
Source: Changnon and Neill, 1968.

rainfall to these sheltered plots and to the open-area plots of this experiment showed quite different yield outcomes.

Certain open-area plots received a 40 percent increase in all rains for a total of 186 mm for June-August 1988, resulting in a yield of 8,424 kg/ha. Almost the same total amount of summer rainfall was applied to certain plots in the shelters. But when water was applied on prescribed rain days for a typical dry summer, the yield was 10,187 kg/ha. This 21 percent yield increase was partially due to the distribution of rain days in the two experiments. Both Julys had the same number of rain days. But in the natural conditions of 1988, most of the rain days occurred in the last half of the month. In the shelters, however, the scant 22.8 mm, which was typical for a dry summer, fell during the critical weeks of 29 June through 12 July.

Monthly Rainfall and Water Treatments

The plots under the mobile shelter were open to natural rainfall from the time the crops were harvested in the fall until June 1 or until the mobile shelters were covered, whichever came later. Plots in the open area were exposed to natural rainfall year-round.

Open-Area Plots

Rainfall on the open-area plots from planting to maturity is shown in table A2. Natural rainfall amounts and distributions are shown in table A3. In June and July 1991 and July 1987 and 1988, more than half of the total monthly rainfall occurred in single rain events. The total "natural" rainfall, shown in both tables A2 and A3, includes three irrigation treatments during June 1988. These were necessary to keep the crop alive during extreme drought that month, when only 8.1 mm of natural rainfall was received.

Mobile Shelter Plots

Water applied to the mobile shelter plots varied among years during the month of June, but was constant for the six precipitation treatments during July and August in all years. The June variations were due to the inability to cover the plots in a timely fashion in 1987, 1988, 1989, and 1990. In 1990, the shelters had already been covered, though not moved into place, when a severe windstorm tore the plastic off them on 30 May. The shelters were not covered again until 8 June. The first treatment date in each of the shelters and the June precipitation amounts for the six treatments are presented in table 5.

Natural rainfall on the open-area plots and on the sheltered plots from October of the preceding year to the date of planting of the current year, and from the date of planting to the first water treatment are presented in table A4. Rainfall from October to the first date of planting was relatively constant for the five years. Rainfall from the date of first planting to the first water treatment was also relatively constant for all the years except for the first planting dates in 1990 and 1991, when the

Table 5. First Day of Water Treatment in June and Total Water Applied in the Mobile Shelter during June

Year	*Shelter number*	*First treatment date*	*Total Water in June (mm)*					
			Dry	*Dry +25%*	*Average*	*Average +25%*	*Wet*	*Wet +25%*
1987	4	8 June	71.1	88.9	101.6	127.0	139.7	174.6
1988	1	8 June	59.9	74.9	91.7	114.6	127.8	159.8
1989	1	3 June	71.1	88.9	101.6	127.0	139.7	174.6
1989	3	8 June	83.6	98.6	115.4	1383	1515	1835
1989	4	8 June	83.6	98.6	115.4	1383	1515	1835
1990	1	14 June	106.6	119.2	129.5	147.8	1643	1913
1990	3	19 June	78.7	84.0	86.6	93.9	119.1	1345
1990	4	19 June	78.7	84.0	86.6	93.9	119.1	1345
1991	1	3 June	71.1	88.9	101.6	127.0	139.7	174.6
1991	3	3 June	71.1	88.9	101.6	127.0	139.7	174.6
1991	4	3 June	71.1	88.9	101.6	127.0	139.7	174.6

plots received more than 100 mm of natural rain. The last planting date in 1991 received the least amount of rain from planting to the first water treatment.

Total Water and Mean Temperature during Crop Growth Stages

Total water on the open plots during June, July, and August varied among the years. On the sheltered plots, the total water applied in July and August was constant, and the total water applied in June was relatively constant with the exceptions noted above. However, plants respond differently to water during different growth stages. Because the crops were planted on different days each year, and because the rate of plant development varied among the years, the water applied during each of the various corn and soybean growth stages differed each year. Therefore, to determine how the timing of increased water affects the plants, the total rainfall and water applied to the plots during each of the growth stages had to be determined. The starting and ending dates of each corn growth stage are shown in table AS, and the dates for soybeans are shown in table A6.

Corn Plots

Total water applied to the mobile shelter and the corn planting date plots during each growth stage is shown in table A7. Rainfall and water applied in stages 1 and 2, planting to tassel initiation and tassel initiation to ear initiation, showed most variation. Corn planted on the early dates received the most water during stage 1. Applications during stages 3 through 6, ear initiation through maturity, were relatively constant The large variation in water applications during the early stages was due to the timing of planting and the covering of the rain shelters.

Unlike the water application in the mobile shelters, the water applied to the open-area corn plots (table A8) showed large year-to-year variations. The two wettest years, 1989 and 1990, showed different patterns of wetness during the growth stages. In 1989, stages 3, 5, and 6 were drier than in 1990; while in 1990, stages 1, 2, and 4 were wetter than in 1989. In the two dry years, 1988 and 1991, stages 4 and 5 were wetter in 1991 than in 1988. These variations illustrate significantly different rainfall distributions during the different growth stages.

Temperature during the five growing seasons also varied greatly (table A9). Generally during stage 1, planting to tassel initiation, the plots planted later experienced higher average maximum and minimum temperatures each year. The later growth stages showed no clear pattern of temperature variation based on date of planting.

Soybean Plots

The total water applied to the mobile shelter soybean plots is shown in table A10. Water applications during stage 1, planting to first unifoliate, varied according to the time between planting and 1 June, or when the shelters were covered, whichever came later. The small variation of water applied in the later growth stages was due to the variation in the calendar dates of the growth stages in the different years (table A6).

In the open-area soybean plots the total rainfall and water application varied more (table A11) than in the mobile shelters. Interesting features of the rainfall treatments are that 1988 was driest during the pure vegetative growth of stages 1 and 2, planting to floral induction, while 1988 and 1990 were relatively dry during flower development in stage 3, floral induction to first flower.

The mean maximum and minimum temperatures during each of the soybean growing stages are presented in table A12.

The average maximum temperatures in 1987, 1988, and 1991 were relatively warm for the pure vegetative growth of stages 1 and 2, planting to floral induction. In 1988, the minimum temperatures during this period were the lowest of the five years. However, 1988 was also the warmest year for stage 4, first flower to physiological maturity, while the coolest was 1990.

Relationships Between Key Weather Variables

Generally, rainfall and air temperatures are inversely related on the daily, monthly, and seasonal scales. To determine the extent of the relationship (dependence) between the various temperature and rainfall values during the different growth stages of corn and soybeans, correlations were computed. These relationships can mask or confuse the effect of different variables during the various growth stages on crop yields. Significant correlations between the weather variables indicate a lack of independence, which violates the assumption of the independence of the predictor variables in multiple regression. The lack of independence of the predictor variables results in uncertainty about the significance of the effect of any single weather condition on the predicted variables.

Correlations of temperature and precipitation are presented for the corn mobile shelter experiment (table A13), the corn planting date study (table A14), the corn open-area study (table A15), the soybean mobileshelterexperiment(tableA16), and the soybean open-area study (table A17). Separate tables are presented for the corn mobile shelter study and the corn planting date study. Because the latter included two planting dates, the correlations of weather variables among the growth stages were different.

Temperature and precipitation (natural and controlled) were least correlated during the first three corn growth stages in all three corn experiments (tables A13-A15). During the last three growth stages (end of row set to maturity), both temperature and rainfall were significantly correlated within and among the stages. This result indicates that the effects of rainfall and minimum temperatures can best be evaluated during the first three growth periods. Attempts to separate the effects of rainfall and temperature during the last three growth stages would be difficult, and uncertainty would exist as to whether the crop was responding to temperature or precipitation.

Water applications during the different soybean growth stages were independent of each other in the mobile shelter study during stages 1, 2, and 3, planting to first flower (table A16). Water applications during stages 3 and 4, floral induction to maturity, were significantly correlated. Therefore, the relative effects of rainfall during the last two growth stages would not be identifiable.

Correlations in the soybean mobile shelter and open-area experiments show different patterns. In the open-area experiment, temperature and rainfall are correlated across all stages of growth (table A17). This indicates that different results can be expected from the two soybean experiments, whereas similar results can be expected in the three corn experiments.

Strong temperature and rainfall correlations among and within the various growth stages do not imply that temperature and/or rainfall in the later stages were caused by temperature and/or rainfall in earlier stages. The correlations do, however, suggest continuity of weather conditions over time. These relationships affect the interpretation of the response of corn and soybean yields and yield components to weather in the different growth stages. Where temperature and rainfall in one growth stage are significantly correlated with temperature and/or rainfall in a different growth stage, the effects of these conditions are less definitive.

The significant correlations among the weather variables during the different growth stages require the use of caution in interpreting results. This is especially true where regression analysis is used to explain yield response to weather. It also requires understanding which yield components can be affected by the weather during each of the different growth stages. For example, the number of rows per ear is determined by stage 3, the end of row set. Correlations of the number of rows with weather variables during stage 4 or later are not meaningful.

Corn Mobile Shelter Experiment

Characteristics of Corn Data

An analysis of variance (SAS, 1990) of the five years of corn data obtained from the mobile shelter experiment was used to assess the effects of the different years, water treatments, and their interactions on: 1) the yield components, including the number of rows per ear, number of kernels per row, and kernel weight; 2) vegetative components, including cob weight and vegetative dry weight; and 3) total grain yield (table A18). All of the crop variables, except for the number of kernels per row, differed significantly (a=0.10) among years and with water treatments. The means of the crop variables for the six water treatments and the five years are presented in table 6. The Duncan multiple range test was used to determine the significant differences among the years and the water treatments. Total grain yield was found to increase with increased water. However, the total yield range was greater among years than between the lowest and highest water treatments averaged over the years. The average vegetative weight of the corn plants also increased as the amount of water increased. Other yield components did not respond to increasing water as consistently as did vegetative weight.

The mean values of the yield components and the total yield for each year and for the six water treatments during each year are shown in table 7. Again, the Duncan multiple range test was used to determine significant differences among the treatments. Significant yield differences due to water treatments occurred only in 1987, 1988, and 1989. Yield components that responded to water treatments were: in 1987 number of rows per ear, number of kernels per row and vegetative mass; in 1988 cob dry weight and vegetative mass; in 1989 number of kernels per row and vegetative mass; and in 1991 cob dry weight.

Table 6. Mean Corn Yield and Yield Components Combined for all Water Received and for All Years, Mobile Shelter Experiments

		No. of rows /ear	No. of kernels /row	Kernel mass (g/plant)	Cob wt. (g/plant)	Vegetative wt. (g/plant)	Grain yield (kg/ha)
Years	1987	12.1 d	37.9 bc	0.189 d	14.8 d	64.5 d	9,775.2 c
	1988	13.6 be	43.2 a	0.310 a	22.4 b	93.0 b	10,916.2 b
	1989	16.5 a	40.8 ab	0.278 b	27.9 a	105.9 a	13,123.5 a
	1990	14.0 b	40.1 ab	0.277 c	22.5 b	79.8 c	10,226.4 bc
	1991	13.1 c	35.9 c	0.263 c	16.9 c	54.4 c	7,569.7 d
Water treatment	Dry	13.6 bc	38.8 a	0.250 b	19.9 bc	69.5 c	9,266.6 c
	Dry + 25%	13.0 c	41.0 a	0.257 ab	19.7 c	72.7 dc	9,022.7 c
	Avg	13.5 bc	39.2 a	0.267 a	21.1 ab	77.1 cd	10,186.6 b
	Avg + 25%	14.1 ab	39.9 a	0.267 a	21.7 a	81.2 bc	10,853.6 ab
	Wet	14.7 a	38.7 a	0.259 ab	21.1 ab	84.6 b	11,293.1 a
	Wet + 25%	14.2 ab	39.9 a	0.263 a	21.9 a	92.1 a	11310.7 a

Notes: Means with the same letter are not significantly different.
Differences between years were determined using the Duncan multiple range test with $a = 0.05$.

Effects of Weather Conditions on Corn

Because the amount of rainfall received during each June, July, and August of the five years was kept constant, the significant year-to-year variation of yield components and final yield indicates that other weather variables affected crop growth. Maximum and minimum temperatures, solar radiation, and evapotranspiration may have affected the corn crop.

Correlations of corn variables with average maximum air temperature, average minimum air temperature, and water received during the six growth stages were computed (table A19) to determine which of these weather conditions had the greatest effect on final crop yield and when these effects were realized. These correlations show that the yield components and final yield are generally inversely related to temperature and positively related to rainfall. Temperature was more highly correlated with final yield and the yield variables than rainfall. This is contrary to common knowledge, which has held that yields respond more to rainfall than temperature. However, this result should be expected because the experiment was designed to apply the same amount of water to the crop each year in six different rainfall treatments. This design resulted in reduced year-to-year variability of rainfall throughout the growth stages, while the temperature varied naturally.

The response of corn yield to the total rain received from planting to maturity is shown in figure 5. In general, total yield increased as rainfall increased. However, there is considerable scatter in the data, and linear regression resulted in an r^2 of only 0.13. Because of the scatter in the data, it is impossible to make any firm conclusions about the optimal level of rainfall necessary for the highest yields. Nevertheless, the data indicate a linear increase across the entire range of rainfall amounts, suggesting that even in the wetter years in east-central Illinois, additional rainfall or irrigation could increase yields.

The yield versus rainfall relationships for the six corn growth stages were generally not strong. However, the correlations (table A19) were highest for stages 3, 4, and 5, ear initiation to end of lag phase. These stages generally occur during late June through July, when corn yield regression models have shown the greatest response to rainfall (Runge, 1968; Thompson, 1986). The highest correlations between precipitation and vegetative dry matter and the number of eared and barren plants also occurred during these stages. The number of rows per ear was the only yield component significantly correlated with rainfall during stage 1, planting to tassel initiation.

The responses of corn yield and the yield components to maximum and minimum temperatures were also examined using linear regression and quadratic fitting to determine how each yield component responded to individual weather variables. The responses with significant linear and quadratic relationships are presented in table A20. In most cases, the degree of curvature of the quadratic function is very small, as evidenced by the small increase of the quadratic R^2 compared to the linear r^2. The strongest quadratic relationships occurred with maximum temperature during stage 2, tassel initiation to ear initiation, and with minimum temperature during stage 3, ear initiation to end of row set.

Interesting quadratic relationships were associated with minimum temperatures and the number of kernel rows per ear, cob dry weight, vegetative dry weight, and total yield. Figure

Table 7. Mean Corn Yield Components and Total Yield by Year and Water Treatment, Mobile Shelter Experiment

Year	*Water treatment*	*Number of rows/ear*	*Number of kernels /row*	*Kernel mass (g)*	*Cob dry weight (g/plant)*	*Vegetative dry weight (g/plant)*	*Grain yield (kg/ha)*
1987	Dry	12.5 ab	35.2 ab	0.185 a	15.3 a	62.3 ab	8,971 ab
	Dry + 25%	10.7 b	50.6 a	0.189 a	14.6 a	65.9 ab	8,638 ab
	Avg	11.1 b	33.2 b	0.197 a	14.0 a	55.1 b	8,002 b
	Avg + 25%	11.8 ab	38.9 ab	0.206 a	15.5 a	58.6 ab	9,896 ab
	Wet	13.6 a	36.0 ab	0.179 a	15.0 a	70.6 ab	11,150 ab
	Wet + 25%	12.9 ab	333 b	0.181 a	14.3 a	73.3 a	11,994 a
1988	Dry	12.7 a	46.1 a	0.301 a	22.0 ab	82.2 b	10,187 ab
	Dry + 25%	12.5 a	43.5 a	0.307 a	20.0 b	82.2 b	9,525 b
	Avg	13.2 a	42.7 a	0.305 a	21.7 ab	90.3 b	10,415 ab
	Avg + 25%	14.6 a	40.1 a	0.317 a	22.5 ab	95.8 ab	11,507 ab
	Wet	14.5 a	42.6 a	0.317 a	23.3 ab	95.8 ab	11,602 ab
	Wet + 25%	14.1 a	44.3 a	0.315 a	25.0 a	111.9 a	12,261 a
1989	Dry	16.3 a	40.9 ab	0.261 a	26.9 a	87.9 b	11,683 b
	Dry+ 25%	16.0 a	37.5 b	0.271 a	26.0 a	93.1 b	11,465 b
	Avg	16.7 a	41.6 ab	0.290 a	29.3 a	107.8 ab	14,284 ab
	Avg + 25%	16.4 a	43.2 a	0.280 a	28.8 a	1103 ab	13315 ab
	Wet	16.5 a	40.5 ab	0.278 a	27.1 a	1093 ab	13,254 ab
	Wet + 25%	16.9 a	41.1 ab	0.285 a	29.6 a	127.1 a	14,741 a
1990	Dry	13.7 a	40.2 a	0.251 a	22.1 a	70.5 a	9,798 a
	Dry + 25%	13.8 a	49.7 a	0.262 a	22.2 a	74.9 a	9,514 a
	Avg	13.8 a	40.3 a	0.276 a	23.1 a	79.5 a	10,462 a
	Avg + 25%	14.6 a	38.4 a	0.267 a	23.0 a	81.7 a	10,665 a
	Wet	14.1 a	42.3 a	0.257 a	22.7 a	84.7 a	10374 a
	Wet + 25%	14.3 a	39.9 a	0.260 a	21.8 a	87.7 a	10446 a
1991	Dry	12.9 a	31.6 a	0.251 a	13.4 b	44.4 a	5,690 a
	Dry + 25%	12.1 a	33.7 a	0.256 a	15.8 ab	47.2 a	5,970 a
	Avg	12.7 a	38.1 a	0.268 a	17.4 a	50.0 a	7,770 a
	Avg + 25%	13.2 a	39.0 a	0.266 a	18.3 a	59.6 a	8,890 a
	Wet	14.6 a	32.3 a	0.261 a	17.3 a	62.5 a	8,580 a
	Wet + 25%	12.9 a	40.9 a	0.274 a	18.8 a	60.4 a	8,510 a

Notes: Means with the same letter are not significantly different at $\alpha = 0.05$. Differences were determined using the Duncan multiple range test

6 shows the total yield response to the minimum temperature during stage 1, planting to tassel initiation. Graphs of the other yield components had similar appearances.

The quadratic relationships made it possible to compute optimal temperatures for different corn growth stages. From planting to tassel initiation, approximately 13°C (table A21) was best for final yield and all yield components except number of kernels per row and kernel mass. The optimal minimum temperature appears to increase to about 18°C as the crop matures.

Wang (1963) showed an optimal minimum temperature that varied with growth stage. During the early growth period, the lower end of the optimal nighttime temperature was approximately 13°C.

During rapid vegetative growth from tassel initiation to silk, stages 2-4, the optimal minimum nighttime temperature was 18 to 24°C. The optimal minimum temperatures observed in this study were approximately the same as Wang's lower optimal thresholds.

Corn Planting Date Experiment

During the first two years of the corn mobile shelter experiment, corn was planted on 31 May 1987 and 12May 1988 due to existing weather and soil conditions. Different plant populations were also used. The 1987 population was 81,500 plants/ha, and the 1988 population was 59,300 plants/ha. Yields averaged 9.78 Mg/ha in 1987 and 10.92 Mg/ha in 1988. The different cultural practices, planting dates, and plant populations made it impossible to determine whether the yield differences were due to the weather or the cultural practices.

Therefore, a new experiment was established in 1989 and continued through 1991 to determine how plant population and planting date would affect the yields from the different water treatments in the mobile shelters. An analysis of variance of the 1989 to 1991 planting date and population data (table A22) shows that only year, date of planting, and rainfall treatments affected the final yields. Significant interactions were observed between the year and the date of planting, and between the year and the date of planting and rainfall treatments.

Although population had no significant effect on final yield, it did have a significant effect (table 8) on the number of rows per ear, the number of kernels per row, the cob dry weight, and vegetative dry weight. The yield components were determined on a per-plant basis, whereas yield was determined on an areal basis over the test plots. These results show that the individual plants and ears were smaller in the high-population plots. However, in the final yield analysis, the higher plant density compensated for the smaller plants and ears. Therefore, at least for the populations tested in this study, a trade-off existed between larger plants and ears associated with lower populations, and smaller plants and ears associated with higher populations.

The earlier planting date resulted in higher yields, more kernels per row, larger kernels as measured by kernel mass, and larger cobs as measured by cob mass (table 8). But plants from this planting were also significantly smaller than plants from the later date, indicating that more energy was going to the growth of the ears than to the leaves and stems in the early growth stages of the early planting.

The means of the yield components and grain yield are shown in table 9 for each of the years and planting date combinations. The 1990 late planting date was near the latest date recommended for corn in east-central Illinois. However, that corn had larger ears and a higher grain yield than either planting date in 1991, when the early growth stages experienced the warmest weather of the three years 1989-1991. These data support the temperature effects observed in the mobile shelter study, where cooler early-season temperatures generally resulted in higher yields. Table A9 indicates that in stage 1, planting to tassel initiation, the early planting dates encompassed cooler temperatures than the later planting dates in the same year.

The six water treatments, ranging from a typical dry summer to a typical wet summer with 25 percent added rainfall, had a significant effect on the number of rows per ear, cob dry weight, plant vegetative size, and final grain yield. Increased rainfall (table 8) generally increased the number of rows per ear, kernel mass, cob size, plant vegetative mass, and final grain yield.

Total corn yield in the planting date experiments was significantly correlated with precipitation during stages 1 and 4, planting to tassel initiation and end of row set to silk (table A23). The number of rows per ear was also linearly correlated with rainfall during stages 2 and 3, tassel initiation to end of row set. As rainfall increased during stage 1, the number of rows per ear also increased. But as rain increased during stage 2, tassel initiation to ear initiation, the number of rows per ear decreased.

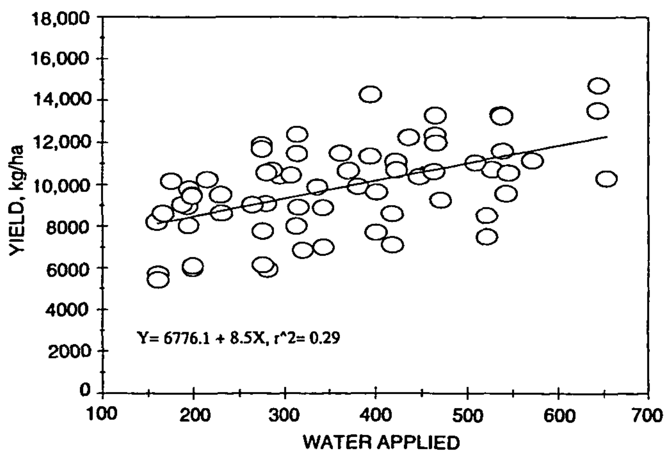

Figure 5. Corn yield response to total rainfall, mobile shelter study

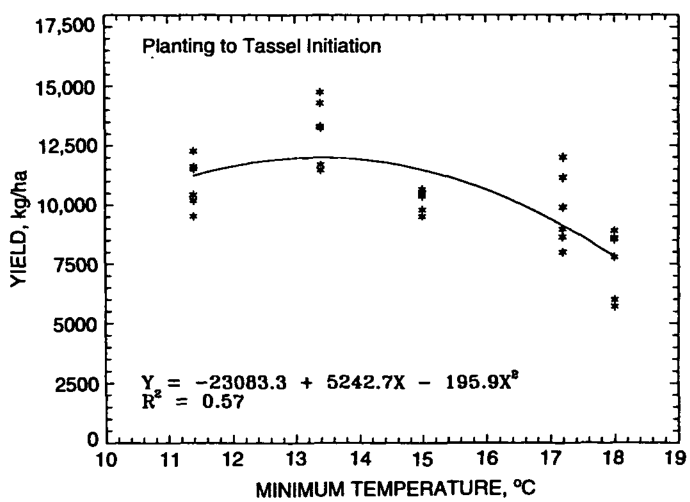

Figure 6. Corn yield response to minimum temperature during stage 1, mobile shelter study

Table 8. Mean Corn Yield and Yield Components, Planting Date and Population Experiment

Treatment		*No. of rows/ear*	*No. of kernels/row*	*Kernel mass (g/plant)*	*Cob wt. (g/plant)*	*Vegetative wt. (g/plant)*	*Grainyield (kg/ha)*
Year	1989	16.0 a	36.9 a	0.208 c	21.7 a	90.4 a	11,172.6 a
	1990	13.7 b	37.1 a	0.262 a	18.8 b	81.7 b	9,706.6 b
	1991	13.7 b	36.0 a	0.239 b	14.5 c	70.4 c	7,399.5 c
Water treatment	Dry	13.7 d	37.2 a	0.228 c	17.0 c	70.5 d	8,1955 d
	Dry + 25%	14.3 cd	37.6 a	0.232 c	183 b	74.3 cd	8,852.9 c
	Avg	14.3 bc	36.3 a	0.232 c	18.0 b	76.0 c	8,9955 c
	Avg + 25%	14.5 bc	36.2 a	0.242 ab	18.5 ab	80.6 b	9,6613 b
	Wet	14.9 ab	35.9 a	0.242 ab	19.2 a	90.8 a	10,2335 ab
	Wet + 25%	15.1 a	36.8 a	0.243 a	19.3 a	92.7 a	10,618.7 a
Population density	59,300 plants/ha	14.9 a	37.6 a	0.238 a	203 a	87.8 a	9,445.8 a
	81,500 plants/ha	14.0 b	35.7 b	0.235 a	16.4 b	73.9 b	9,406.7 a
Date of planting	Early	14.5 a	38.7 a	0.240 a	19.0 a	76.4 b	10340.7 a
	Late	14.4 a	34.7 b	0.233 b	17.7 b	85.3 a	8,511.8 b

Notes: Significant differences were determined using the Duncan multiple range test with a = 0.05.
Means with the same letter are not significantly different.

During stages 2 and 3 the ear begins to form, and the number of rows per ear is determined by the end of stage 3.

The linear correlation between the number of kernels per row and rainfall is significant only during stage 1. But the mass of the kernels also affects total yield. In this experiment, a negative relationship was found between rainfall and kernel mass during stage 1. That negative correlation was of the same magnitude as the positive correlation between rainfall and the number of kernels per row. This indicated that the corn plants' ability to produce carbohydrate for grain yield was limited, and that the plants tried to fill all kernels equally. With more kernels per ear, the mass of individual kernels was reduced unless the carbohydrate supply was increased.

Most of the corn yield components showed strong negative correlations with temperature (table A23) during the earlier growth stages: higher temperatures resulted in smaller plants, ears, and lower total yields.

Graphs of the planting date study revealed quadratic responses between maximum and minimum temperatures during stage 3, ear initiation to end of row set, and the number of kernels per row (figure 7). The optimal minimum temperature was 18.4 °C, and the optimal maximum temperature was 29.5°C. Because of the high correlation between the maximum and minimum temperatures during this growth stage (table A14), it was impossible to determine whether the number of kernels per row responded to the maximum or the minimum temperature. However, the maximum temperature relationship explains slightly more of the variance (adjusted R^2 = 61.6 percent) than the minimum temperature relationship (adjusted R^2 = 59.5 percent).

Significant quadratic relationships were found between vegetative mass and minimum temperature at stage 4, end of row set to silking, and between vegetative mass and maximum temperature at stage 5, silking to end of lag phase (figure 8). The optimal minimum temperature was 18°C, and the optimal maximum temperature was 28°C. Again, the maximum temperature in stage 5 was highly correlated to the minimum temperature at stage 4. Therefore, the actual physiological significance of the individual relationships was not clear. However, during stage 4, the last ten leaves are enlarging and a major portion of the stem is being grown. Therefore, the minimum temperature during the early growth period may be affecting the rate of nighttime respiration (Grozesiak et al., 1981). In the morning following a cool night of below-optimal temperature, photosynthesis recovery slows, thus reducing the total amount of carbon fixed (Grezesiak et al., 1981). The results may lead to the design of studies to understand more fully the relationship between temperature and corn growth during these stages.

Quadratic relationships were also found between total yield and maximum temperature during stage 5, silk to end of lag phase, and stage 6, end of lag phase to maturity. Optimal

Table 9. Interaction of Year and Date of Planting on Corn Yield and Yield Components, Planting Date Experiment

Year	Date of planting	No. of rows /ear	No. of kernels /row	Kernel mass (g/plant)	Cob wt. (g/plant)	Vegetative wt. (g/plant)	Grain yield (kg/ha)
1989	13 May	16.1 a	38.9 a	0.220 a	23.0 a	89.6 a	12,490.1 a
	31 May	15.9 a	35.0 b	0.197 b	20.3 b	91.1 a	9,855.0 b
1990	24 May	14.3 a	39.0 a	0.243 b	18.8 a	77.9 b	10,269.0 a
	5 Jun	13.1 b	35.2 b	0.278 a	18.9 a	85.7 a	9,1443 b
1991	15 May	13.2 b	38.1 a	0.256 a	15.3 a	61.8 b	8,262.9 a
	29 May	14.2 a	33.9 b	0.223 a	13.7 b	79.0 a	6,536.0 b

Notes: Significant differences were determined using the Duncan multiple range test with $\alpha = 0.05$. Means with the same letter are not significantly different.

maximum temperatures were 27.8°C during stage 5 and 26.0°C during stage 6. These stages normally occur during July and August, the wannest months of the summer, when average maximum temperatures are 29.6°C in July and 28.3°C in August. These optimal temperatures suggest that the highest yields would occur when July and August are cooler than normal.

Soybean Mobile Shelter Experiment

Analysis of variance of the soybean mobile shelter data revealed that both the years and the rainfall had a significant effect on yield, number of pods with beans, pod mass, and dry vegetative weight (table A24). The number of pods without beans varied with year only. Response of the number of pods with beans, vegetative mass, and yield varied with rainfall by year. This interaction suggests that the optimal rainfall value would depend upon other weather factors during the growing season. Table 10 presents the mean yield component and yield data by year and by rainfall treatment. Yields were lowest in 1988 and highest in 1989. The 1989 yields were not significantly different from the 1990 and 1991 yields at the 5 percent level of significance using the Duncan multiple range test. The typical wet summer with 25 percent added water produced yields that were significantly different from the other five treatments. Yields for the wet summer treatment were significantly different from those for the dry summer treatment, but not significantly different from the dry plus 25 percent, average, and average plus 25 percent treatments. Final yield and plant size increased as the crop received more water. Vegetative mass was significantly greater under the wet summer and wet summer plus 25 percent treatments. The dry summer treatment produced significantly less vegetative mass than the other five treatments.

To determine soybean growth stages, temperature and photoperiod data collected during the five years of the experiment were input to the SOYGRO model (Wilkersonetal., 1983) to describe soybean phenology according to the model of Jones et al. (1991). Mean minimum and maximum temperatures and total water applications during the four soybean growth stages were correlated with yields and yield components. The linear correlations during the four growth stages are shown in table A25. Total yield was found to be positively correlated with precipitation during stages 1 and 4 at the 1 percent probability level. Total yield was found to be inversely related to maximum and minimum temperatures in stage 4. The significant correlations with temperature were all negative, indicating that yields increased with cooler summer temperatures.

Maximum and minimum temperatures in the last growth stage and rainfall in stage 2 were significantly correlated with the numbers of pods with beans. The temperature correlations were negative, indicating that high summer temperatures reduced the number of pods with beans. A high negative correlation was also found between maximum temperature and the number of pods without beans during stages 1 and 4. Because both the number of pods with and without beans were reduced, higher summer temperatures in fact reduced the number of flowers able to set pods and reduced the number of pods that failed to fill. The yield components and final yield were generally negatively correlated with temperatures, while vegetative dry weight increased with increasing minimum temperature during the vegetative growth stages. This finding indicates that temperatures favorable for vegetative growth reduce final yield by reducing the number of pods that are set and eventually filled.

Rainfall amounts were positively correlated with vegetative growth during stages 1,3, and 4, but not during stage 2, first unifoliate to floral induction. At this stage, the number of pods both with and without beans were both positively correlated with rainfall. The correlation of rainfall with the number of pods with and without beans during stage 2, normally in June, indicated the importance of good soil moisture as the soybean crop enters floral induction.

The significant correlations between rainfall and final yield during stages 1, 3, and 4 indicate that the soybean crop was responsive to additional water applications during most growth stages. Therefore, yield increases should be expected with rainfall increases throughout the growing season.

The linear correlations indicate that the number of pods both with or without beans decreased as maximum and minimum temperatures increased. Plots of the data (figure 9) indicate that a quadratic relationship might be more appropriate for the number of pods with and without beans. The number of pods with beans was observed to increase with maximum temperatures below 29°C (figure 9a) and with minimum temperatures below 18°C (figure 9b). Above these thresholds, the number of pods with beans was relatively constant with temperature. This interpretation must be used with caution because of the small data set and the single observation for temperatures above 18°C (minimum) and below 29°C (maximum). Hume and Jackson (1981) reported that soybeans would not develop pods when temperatures dropped below 15°C. Therefore, extrapolation of this relationship to temperatures below 16°C would result in erroneous conclusions. The anticipated curve would be a plateau from below 16°C to approximately 15°C, then the number of pods would decrease as the temperature continued to drop.

Plots of vegetative mass and minimum temperature also showed a curvilinear relationship during the four growth stages (figure 10). During stage 1, planting to first unifoliate, minimum temperatures below 12.5°C reduced the final vegetative mass, while a plateau existed above 12.5°C. The relationship during stages 2 and 3, first unifoliate to first flower, were similar. A threshold minimum temperature of 14°C was observed during stage 2, and 16.5°C during stage 3. From first flower to maturity, stage 4, the relationship was more quadratic,

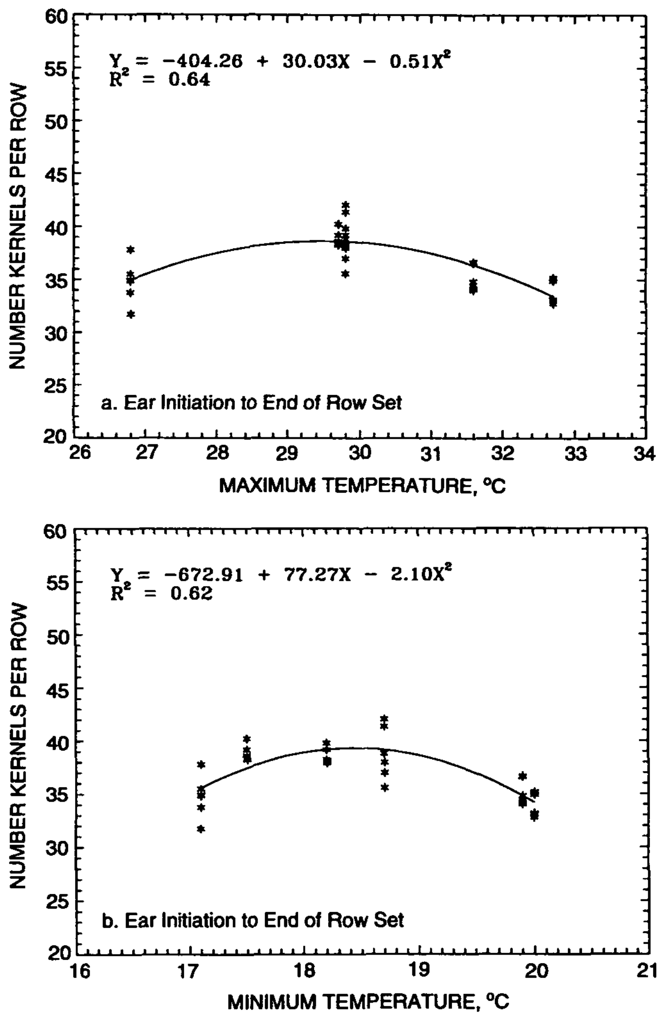

Figure 7. Number of kernels per row as a response to maximum temperature (a) and minimum temperature (b) during stage 3, planting date study

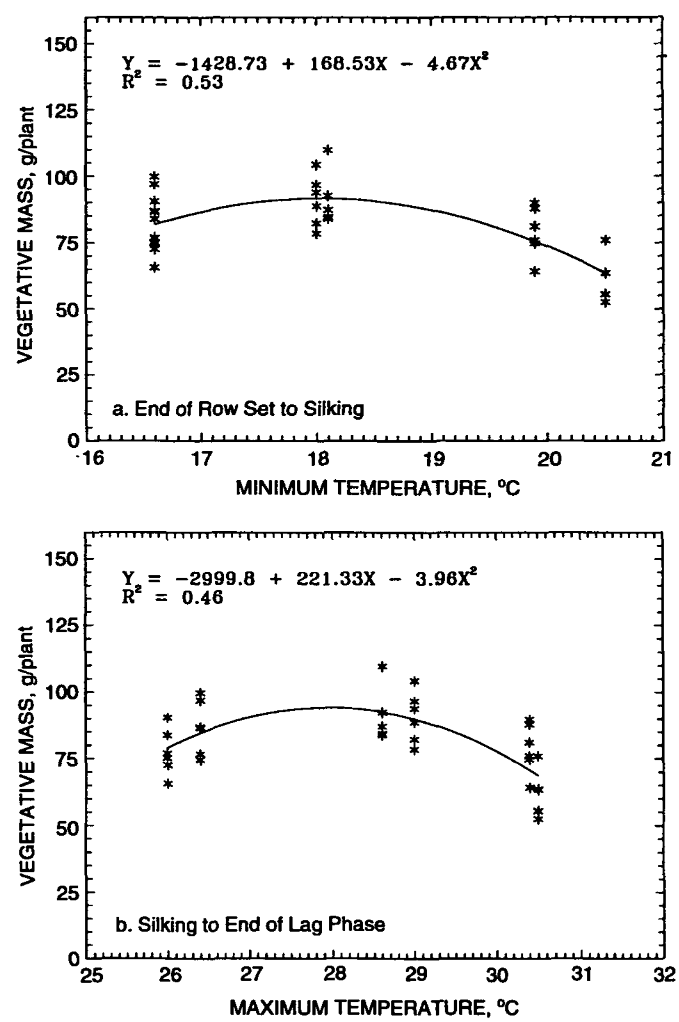

Figure 8. Corn vegetative mass as a response to minimum temperature during stage 4 (a) and maximum temperature during stage 5 (b), planting date study

Table 10. Mean Soybean Yield and Yield Components for All Water Received, Mobile Shelter Experiment

	Level	*No. pods with beans*	*No. of pods without beans*	*Seed wt./pod (gm)*	*Vegetative wt. (kg/ha)*	*Grain yield (kg/ha)*
Year	1987	24.2 cd	1.1 b	0.367 a	639.7 b	2,712.5 b
	1988	34.8 b	0.6 b	0.338 a	521.7 c	2,428.7 c
	1989	21.9 d	0.6 b	0.390 a	6823 a	3,1023 a
	1990	65.7 a	7.4 a	0.386 a	539.7 c	2,948.7 ab
	1991	28.0 c	0.7 b	0.347 a	720.8 a	2,919.1 ab
Water treatment	Dry	30.9 b	1.9 a	0.366 b	532.8 d	2,582.0 c
	Dry + 25%	32.7 b	1.9 a	0.338 b	586.0 c	2,732.2 bc
	Avg	34.1 ab	1.9 a	0.329 b	612.6 c	2,6963 bc
	Avg + 25%	40.1 a	2.2 a	0.350 b	622.1 bc	2,794.5 bc
	Wet	32.4 b	2.2 a	0.447 a	665.3 ab	2,938.0 b
	Wet + 25%	39.4 a	2.4 a	0.363 b	706.1 ab	3,190.7 a

Notes: Differences between years were determined using the Duncan multiple range test with $\alpha = 0.05$. Means with the same letter are not significantly different.

with an optimal minimum temperature near 17.7°C. Above and below this optimal minimum temperature, vegetative mass declined. When the maximum temperature exceeded 30.5°C during stage 3, floral induction to first flower, vegetative mass also declined (figure 11). As with the corn growth stages, care must be used in applying these data beyond this experiment because of the strong correlations between temperature during the various growth stages.

Total soybean yield responses to temperature were similar to those observed for vegetative mass (figures 12 and 13). The threshold minimum temperature for stage 1, from planting to first unifoliate, was approximately 12°C (figure 12a); for stage 2, first unifoliate to floral induction, it was 14°C (figure 12b); and for stage 3, floral induction to first flower, it was 16.5°C (figure 12c). For stage 4, first flower to maturity, total yield decreased with minimum temperatures above 17.8°C. However, this may be a maximum temperature response (figure 13). With maximum temperatures above 30°C, the final yield decreased to a greater extent than with minimum temperatures above 17.8°C. Also, the 30°C maximum temperature represents a threshold for high-temperature stress in summer crops.

Corn Open-Area Experiment

The 1987 open-area corn study was damaged beyond use by a storm. Therefore, analysis of variance of the corn data from the open-area experiment includes the years 1988 through 1990. Response of four crop variables (the number of rows per ear, kernels per row, kernel mass, and total yield) differed significantly among years (table A26). Rainfall treatments had an impact only on the number of rows per ear. However, analysis of variance using only the first four rainfall treatments (table A27) revealed that the number of kernels per row and total corn yield also showed significant responses to rainfall.

The mean yield components and mean total yield for each rainfall treatment (table 11) show the differences between the numbers of rows per ear, kernels per row, and yield among the years. The 1988-1990 yearly groups include all ten water treatments, whereas only the first four are included in the 1988-1991 yearly groups. Likewise, the ten water treatments noted in table 11 cover only the three years 1988-1990, whereas water treatments 1-4 at the end of the table include four years of data (1988-1991).

Kernel mass was the only yield component that did not vary with year. The water treatments did not significantly affect the numbers of rows per ear or kernels per row. In fact, kernel mass tended to decrease with increased water applications. The different water treatments produced larger yield variations among years than within years. Because the total amount of water received by the plots each year was not constant, the ten treatments applied varied accordingly. The total water received each year ranged from lows in 1988 and 1991, to highs in 1989 and 1990. In the wet years, total grain yield, vegetative mass, and the number of kernels per row were greater than in the dry years. The highest and lowest yields for the ten water treatments over the years were significantly different. However, they did not correspond to the highest and lowest rainfall treatments within each year.

Results of the Duncan means test, a=0.05, (table A28) reveal that the water treatments within years had few significant effects on yields and yield components. Some differences due to water treatments were observed in 1988, 1989, and 1990. However, the higher yields do not correspond to the higher water treatments. The vegetative components of cob dry weight

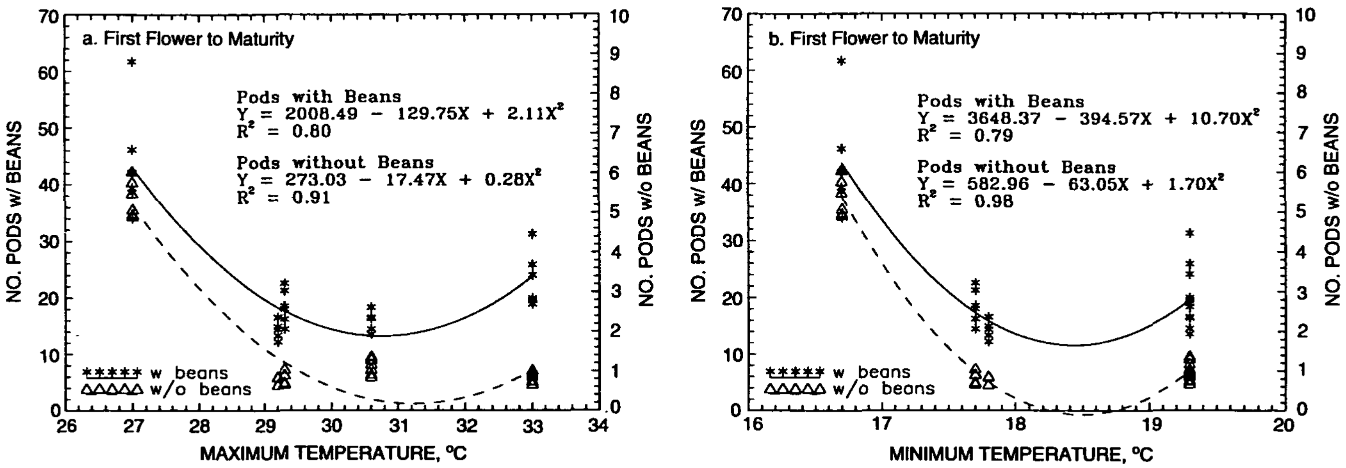

Figure 9. Number of pods with and without soybeans as a response to maximum temperature (a) and minimum temperature (b) during stage 4, mobile shelter study

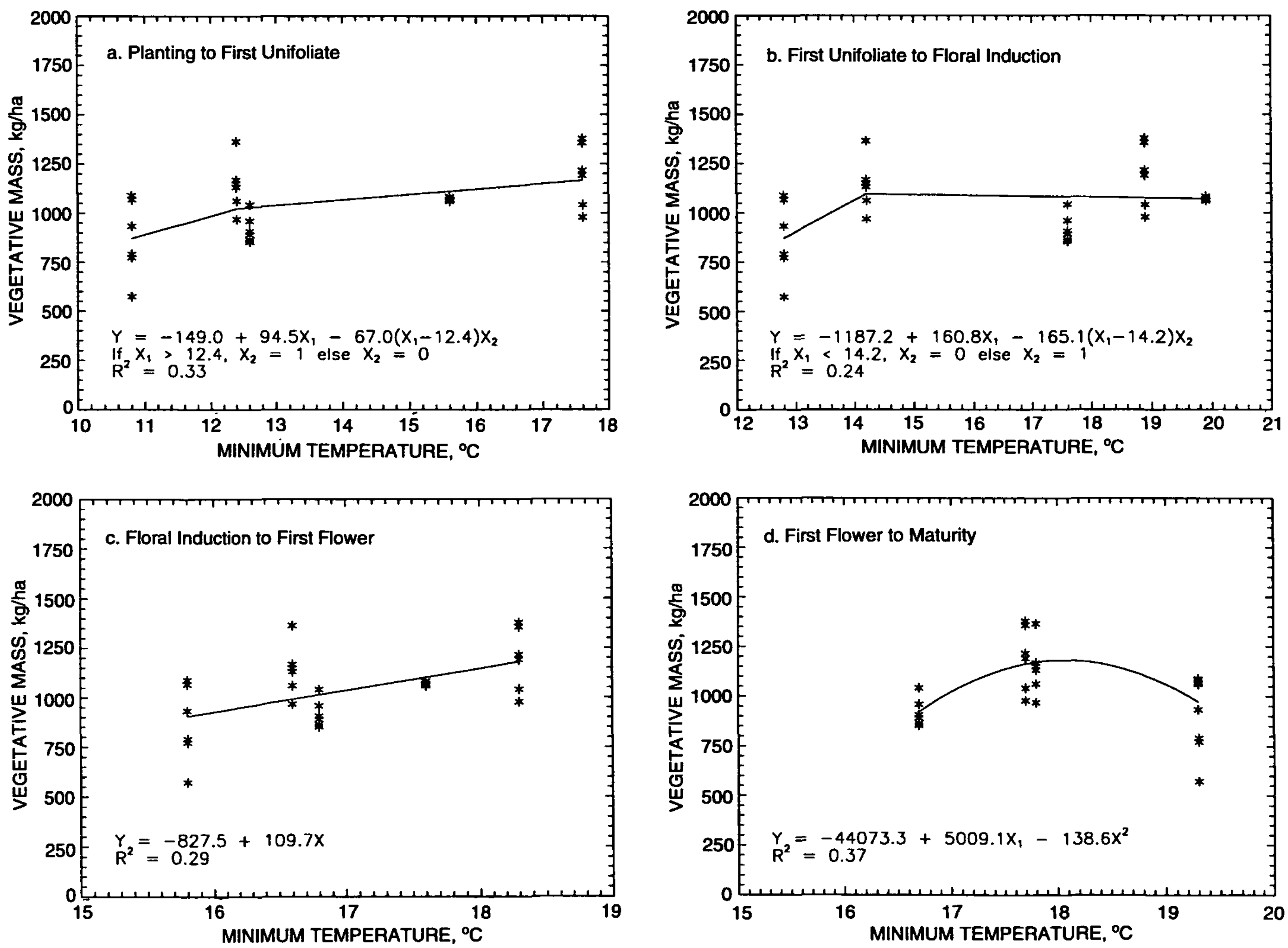

Figure 10. Soybean vegetative mass as a response to minumum temperature during stages 1-4 (a-d), mobile shelter study

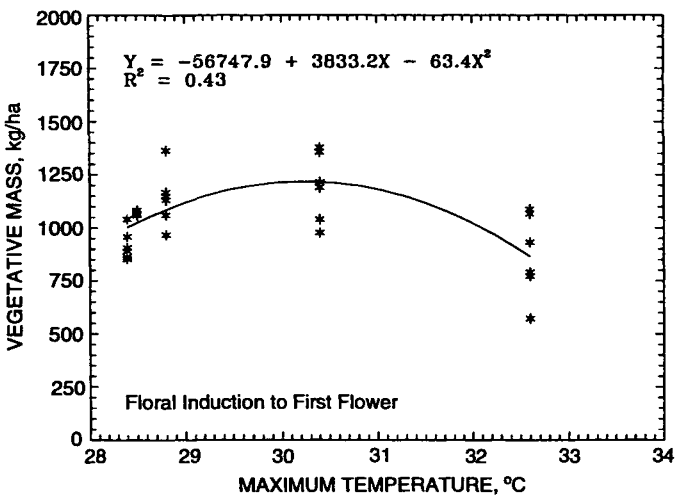

Figure 11. Soybean vegetative mass as a response to maximum temperature during stage 3, mobile shelter study

and vegetative dry weight varied significantly only in 1989. Data were not available for 1988.

Correlations between maximum and minimum temperatures and precipitation, and the yield components and final yield during the six stages of corn growth (table A29) reveal that corn yield components were significantly correlated with almost all the weather variables during the stage 1, planting to tassel initiation. The number of rows per ear was correlated with all the weather variables during stages 1 and 2, except for rainfall in stage 2. The number of kernels per row and kernel mass were correlated with almost all weather variables in all six growth stages. Total yield was significantly correlated with rainfall in stages 1, 3, 5, and 6, planting to tassel initiation, ear initiation to end of row set, and silk to maturity. Vegetative mass was significantly correlated with rainfall in stages 3-6. The relationship was negative during stage 4, end of row set to silk, indicating that increased rainfall during this period resulted in smaller plants in the open-area study. In the planting date and mobile shelter studies, however, rainfall was positively corre-

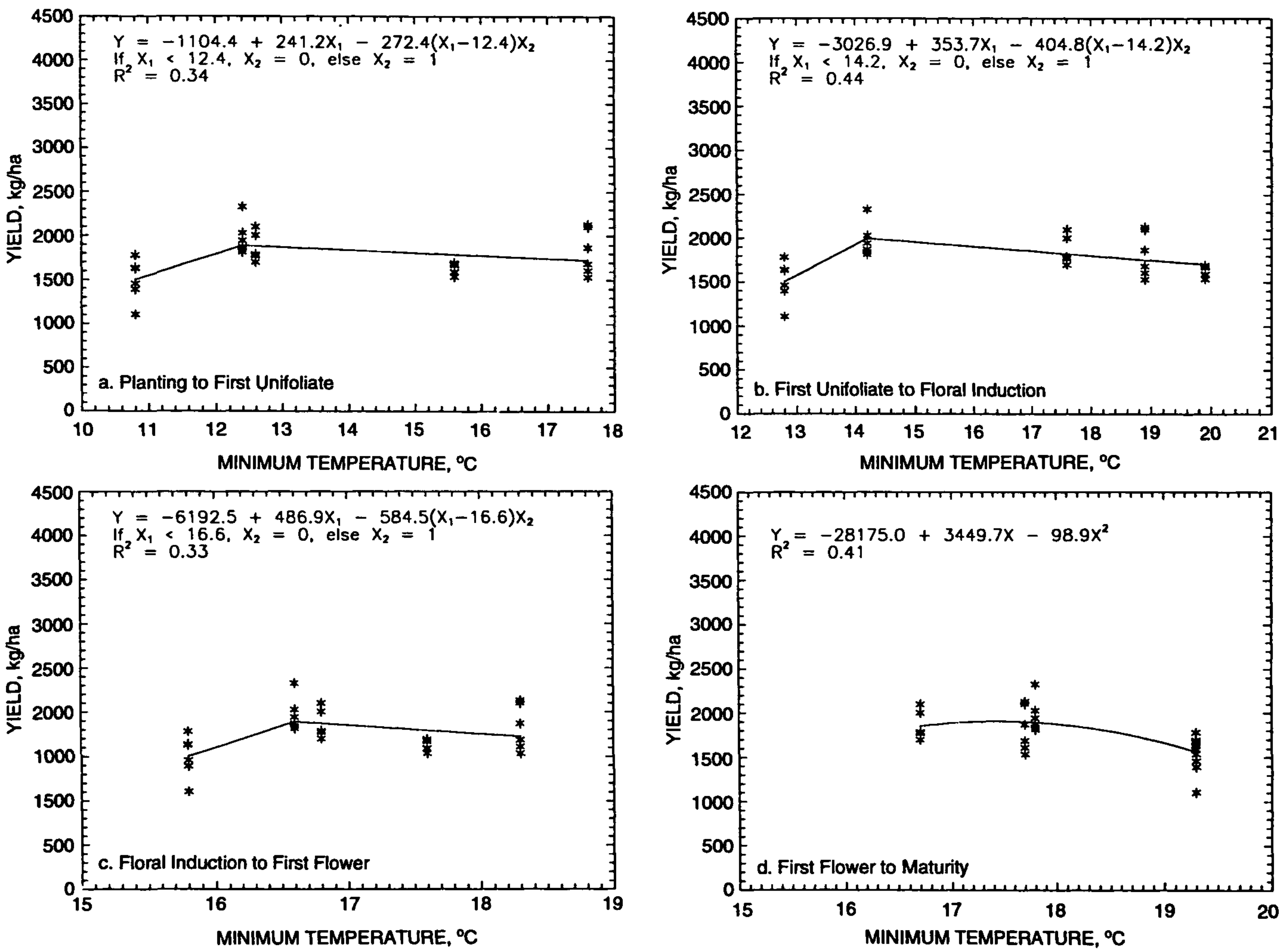

Figure 12. Soybean yield response to minimum temperature during stages 1-4 (a-d), mobile shelter study

Table 11. Mean Corn Yield and Yield Components Combined for All Water Received and for All Years, Open-Area Experiment

		No of rows/ear	No. of kernels/row	Kernel mass (g/plant)	Cob wt. (g/plant)	Vegetative wt (g/plant)	Grain yield (kg/ha)
Year	1988	11.8 c	34.4 b	0.333 a	-	-	7,279.1 c
	1989	16.2 a	42.0 a	0.329 a	28.5 a	89.4 a	14,175.9 a
	1990	15.1 b	43.0 a	0.256 a	23.5 b	70.5 b	12,131.1 b
Water Treatment	1	13.9 a	42.1 a	0.321 a	27.3 ab	81.3 abc	11,070.0 ab
	2	14.2 a	38.6 a	0.307 ab	24.5 c	81.6 abc	10,212.9 b
	3	14.0 a	40.0 a	0.318 a	26.3 abc	87.1 a	11,199.1 a
	4	14.6 a	40.2 a	0.303 ab	25.8 abc	73.5 bc	11,485.7 ab
	5	14.6 a	39.6 a	0.310 a	25.5 abc	79.9 abc	11,456.7 ab
	6	14.1 a	39.2 a	0.316 a	26.1 abc	74.8 bc	10,843.1 ab
	7	15.1 a	39.0 a	0.288 b	24.9 bc	71.7 c	11,1833 ab
	8	14.1 a	39.2 a	0.313 a	27.7 a	84.9 ab	113917 ab
	9	14.5 a	39.9 a	0.303 ab	25.9 abc	80.9 abc	11,494.9 ab
	10	14.3 a	40.4 a	0.312 a	25.9 abc	83.6 ab	11,616.4 a
Year	1988	11.4 c	36.3 b	0.344 a	-	-	6,918.4 c
	1989	16.3 a	42.0 a	0.326 a	28.6 a	90.4 a	143053 a
	1990	14.9 b	42.4 a	0.266 a	23.3 b	71.3 b	11,752.1 b
	1991	15.4 b	36.0 b	0.199 a	14.6 c	60.6 c	7,512.7 c
Water Treatment	1	14.2 a	40.6 a	0.292 a	23.1 a	75.6 a	10,197.6 ab
	2	14.4 a	38.0 a	0.280 ab	21.3 b	75.2 a	9,536.3 b
	3	14.4 a	39.0 a	0.287 ab	22.2 ab	76.5 a	10,204.6 ab
	4	14.9 a	39.1 a	0.276 b	22.2 ab	69.2 a	10,550.0 a

Notes: Means with the same letter are not significantly different.
Differences between treatments were determined using the Duncan multiple range test with $\alpha = 0.05$.
Precipitation treatments:
1. Natural rainfall.
2. Increase all daily rains 10 percent
3. Increase all daily rains 25 percent
4. Increase all daily rains 40 percent
5. Increase all daily rains of 2.54 mm to 25.4 mm by 10 percent (moderate rain).
6. Increase all daily rains of 2.54 mm to 25.4 mm by 25 percent (moderate rain).
7. Increase all daily rains of 2.54 mm to 25.4 mm by 40 percent (moderate rain).
8. Increase all daily rains above 25.4 mm by 10 percent (heavy rain).
9. Increase all daily rains above 25.4 mm by 40 percent (heavy rain).
10. Increase all daily rains less than 254 mm by 40 percent (light rain).

lated with plant size during stage 4, although the correlation was not significant

Curvilinear relationships were found between yield and yield components, and maximum and minimum temperatures. The number of rows per ear declined when the minimum temperature dropped below 13.5°C during stage 1, planting to tassel initiation (figure 14a), and below 15.5°C during stage 2, tassel initiation to ear initiation (figure 14b). The number of kernels per row decreased as temperatures rose above 29°C during the lag phase in stage 5, and above 28°C (figure 15b) during grain fill in stage 6. This effect during stage 6 was due to the persistence of weather conditions between stages 5 and 6 (table A15). The reduction in the number of kernels per row during the lag phase would be consistent with the effects of high temperatures on grain set in corn as reported by Herrero and Johnson (1981) and Jones et al. (1981, 1984, 1985).

Curvilinear relationships were also indicated between the number of kernels per row and the temperature during stages 1 and 2, planting to ear initiation. During stage 1, planting to tassel initiation, a temperature plateau existed from 13.5 to

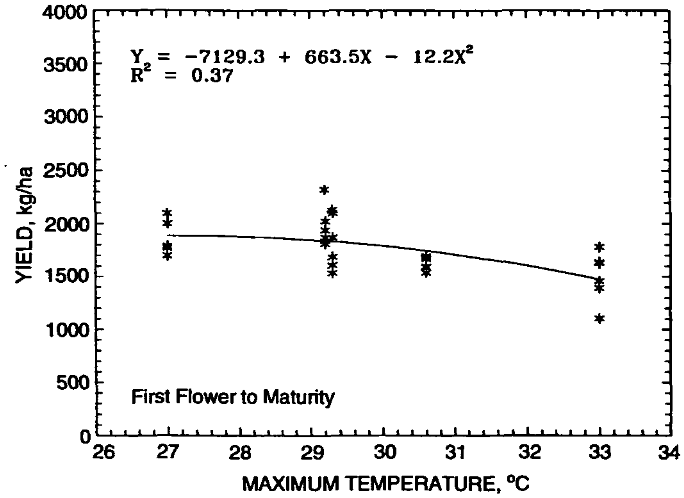

Figure 13. Soybean yield response to maximum temperature during stage 4, mobile shelter study

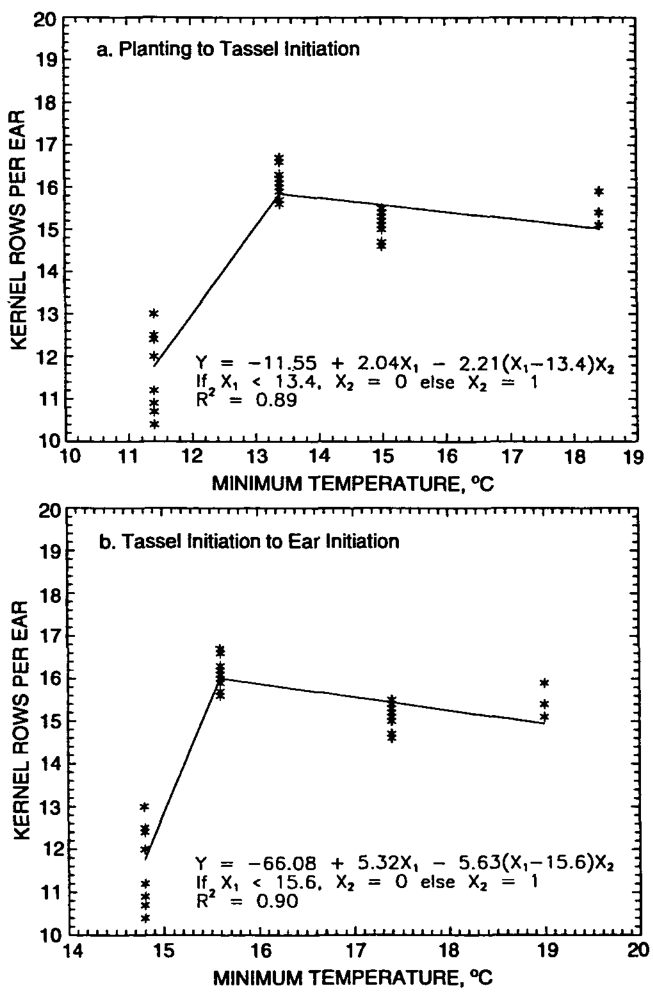

Figure 14. Number of rows per ear as a response to minimum temperature during stages 1-2 (a-b), open-area study

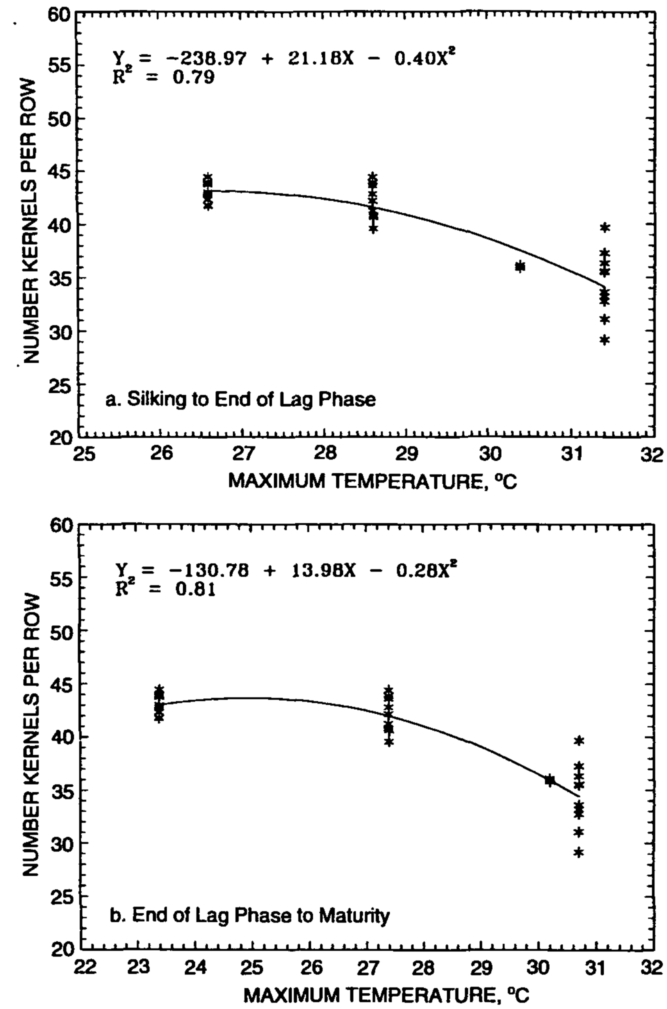

Figure 15. Number of kernels per row as a response to maximum temperature during stages 5-6 (a-b), open-area study

15°C, and the number of kernels per row decreased above and below these temperatures (figure 16a). During stage 2, tassel initiation to ear initiation, the optimal maximum temperature rose to 15.5 to 17.5°C (figure 16b). Additional studies are needed to confirm and define these optimal temperature ranges more accurately.

Kernel mass tended to decrease as the minimum temperature rose above 13.5°C during stage 1, planting to tassel initiation (figure 17a) and above 16°C during stage 2, tassel initiation to ear initiation (figure 17b). Optimal minimum temperature for kernel mass during stage 4, end of row set to silk, was 18 to 19°C (figure 17c) and 16 to 17°C during stage 6, end of lag phase to maturity (figure 17d). Kernel mass is being determined during stage 6, so it is more likely that the temperature response in this last growth stage would have a more obvious physical connection.

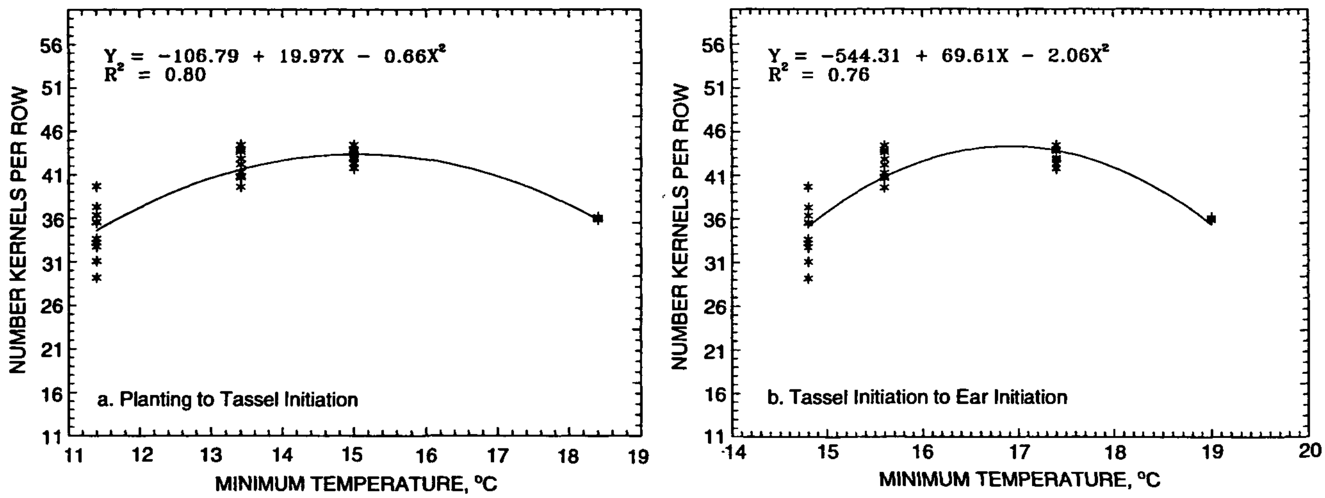

Figure 16. Number of kernels per row as a response to minimum temperature during stages 1 -2 (a-b), open-area study

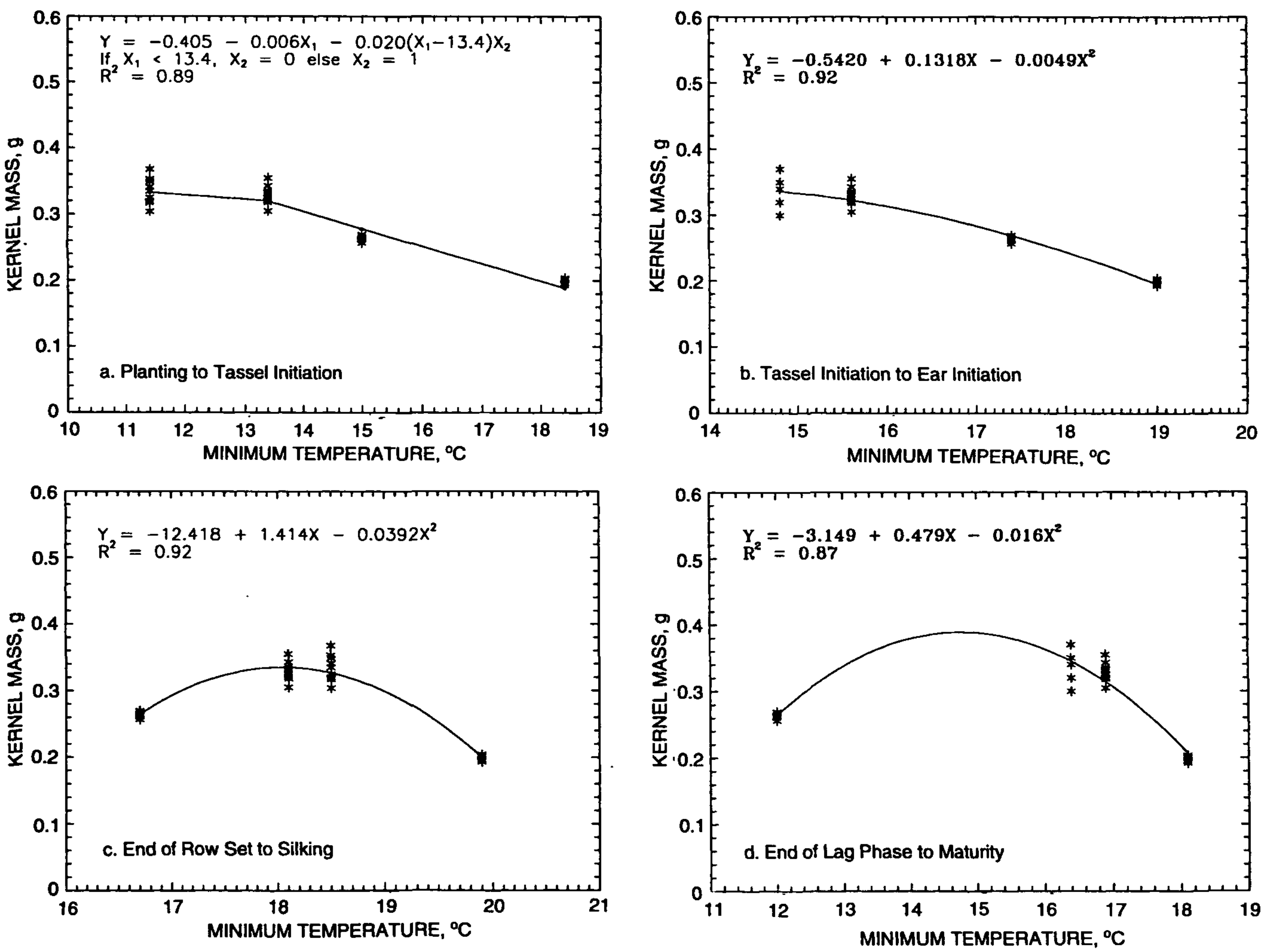

Figure 17. Kernel mass as a response to minimum temperature during stages 1 (a), 2 (b), 4 (c), and 6 (d), open-area study

Final yield was also curvilinearly related to maximum and minimum temperatures. The optimal minimum temperature in stage 1, planting to tassel initiation, was approximately 13.5°C, (figure 18a) and yields decreased rapidly below or above this level. During stage 2, tassel initiation to ear initiation, the optimal temperature was 15.5°C (figure 18b).

Curvilinear relationships between maximum temperature and final yield were indicated in four of the six corn growth stages (figure 19). Final yield decreased when maximum temperature rose to 28°C and then leveled off during stage 1, planting to tassel initiation (figure 19a). Final yields benefited from an optimal maximum temperature of about 30°C at stage 3, ear initiation to end of row set (figure 19b). Above 30°C, yields decreased rapidly; below 30°C, the rate of decrease slowed. Finally, yields were greatest when maximum temperatures averaged near 29°C during stage 5, silk to end of lag phase (figure 19c), and near 27°C during stage 6, end of lag phase to maturity (figure 19d). Again, temperatures higher than 30°C reduced grain yield rapidly.

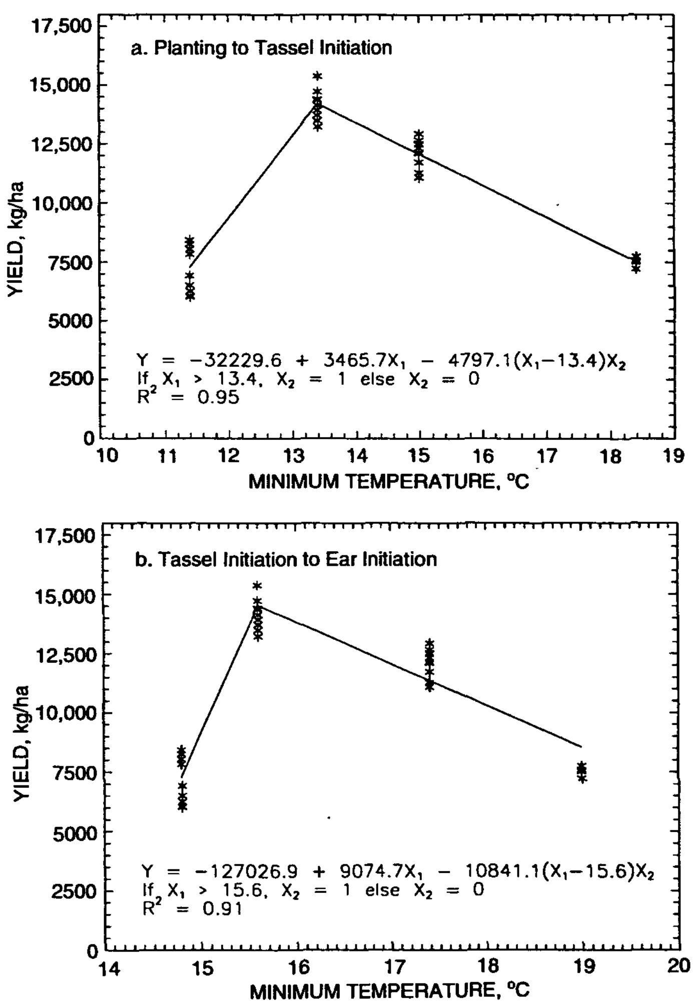

Figure 18. Corn yield as a response to minimum temperature during stages 1 -2 (a-b), open-area study

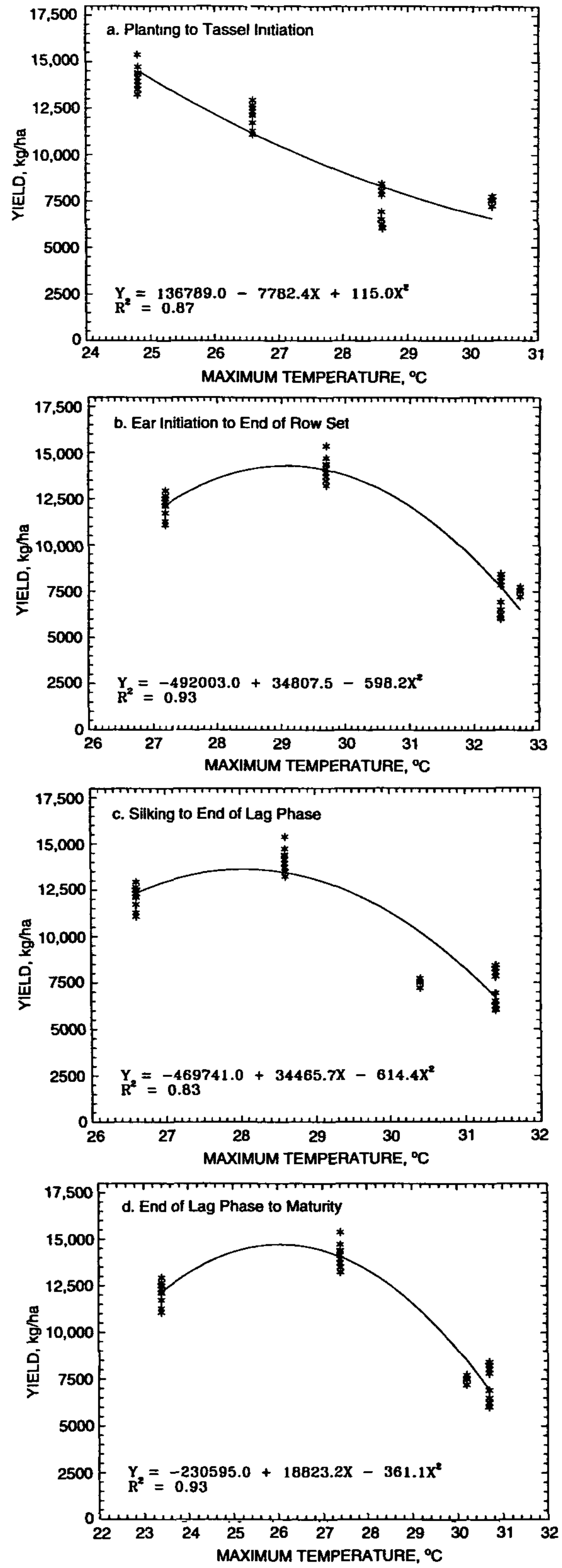

Figure 19. Corn yield as a response to maximum temperature during stages 1 (a), 3 (b), 5 (c), and 6 (d), open-area study

Corn yields resulting from water received by the crop throughout the growing season are shown in figure 20. The values for the two wet years (1989 and 1990) and the two dry years (1988 and 1991) are obvious.

A plot of the yields and the water applied during the grain fill period in stage 6, end of lag phase to maturity, indicates the importance of rainfall during this period (figure 21). In the two wet years, the highest yield was produced when approximately one-half of the total rainfall occurred during grain fill. Although the yield difference does not appear to be great, the mean yield due to the various water treatments during the two wet years, 1989 and 1990, differed by 2,045 kg/ha. In the dry years, when the crop also received approximately one-half of its total water supply during the grain fill period, the yield difference was only 594 kg/ha.

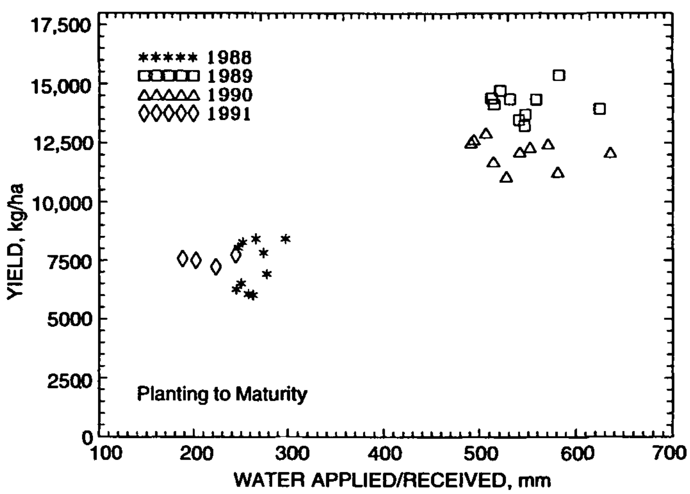

Figure 20. Corn yield as a response to total rainfall, open-area study

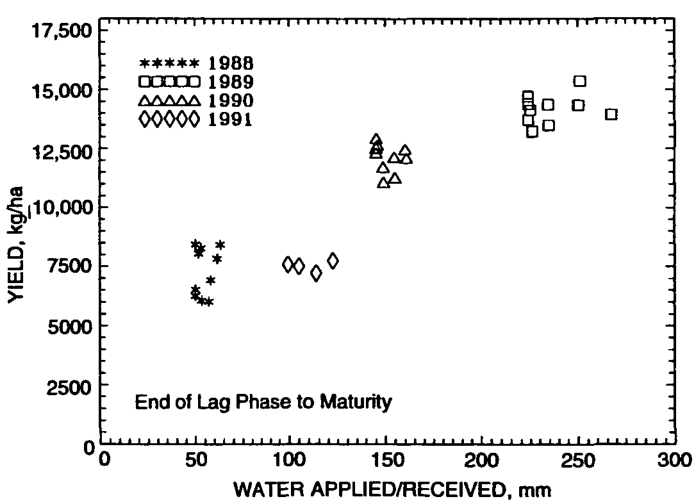

Figure 21. Corn yield as a response to rainfall during the grain fill period of stage 6, open-area study

Soybean Open-Area Experiment

The rainfall treatments in the open-area soybean plots had a significant effect (table A30) on the number of pods with beans. However, rainfall additions did not affect total yield, dry vegetative weight at harvest, the number of pods without beans, or seed mass per pod. Soybean yields and all the yield components varied significantly with year. When the effects of the water treatments were combined over all the years, the highest and lowest yields in response to the ten treatments were significantly different (table 12). The lowest yield was 2,239.6 kg/ha (treatment 8), and the highest was 2,533.5 (treatment 1). Note that the largest soybean yield was associated with natural rainfall (the lowest amount of water applied each year). The lowest yield is associated with a 10 percent increase to all rains greater than 25.4 mm (treatment 8). The average yield differences in response to the various water treatments were small enough to conclude that increasing rainfall had an insignificant effect on soybean yields in any given year.

Yields and yield components differed in each year (table 12). The largest yield occurred in 1989 and the smallest in 1987. The fewest pods were set on plants in 1987, which was a warm moist summer, and the largest number in 1990, a cool wet summer. The second largest number of pods was set in 1988, a hot dry summer. The two years with the highest yields, 1989 and 1990, were both cooler than normal, while the lowest yields occurred in the two summers that were hotter than normal, 1987 and 1988.

A significant positive linear correlation (table A31) exists between total soybean yield and rainfall during stage 1, planting to first unifoliate. Total yield was negatively correlated with rainfall during stage 4, first flower to maturity. Vegetative dry weight at harvest was also positively correlated with rainfall during stage 1. The numbers of pods with and without beans were negatively correlated with rainfall during stages 1, 3, and 4, planting to first unifoliate and floral induction to maturity. However, the total number of pods was positively correlated with rainfall during stage 3, first unifoliate to floral induction.

All significant correlations between maximum and minimum temperature and total yield and yield components were negative. During stage 1, planting to first unifoliate, the seed mass per pod decreased as maximum temperature increased (figure 22a). Three optimal minimum temperatures were defined for greatest seed mass per pod:

1. 12.5°C during stage 1, planting to first unifoliate (figure 22b)
2. 14°C during stage 2, first unifoliate to floral induction (figure 22c)
3. 17.8°C during stage 4, first flower to maturity (figure 22d)

The first two optimal minimum temperatures are not independent of each other because the minimum temperatures between the two stages are correlated. However, the minimum temperature in stage 4 was independent of the first two stages. Thus, the

Table 12. Mean Soybean Yields and Yield Components Combined for all Water Treatmens, Open-Area Study

		No. of pods with beans	*No. of pods without beans*	*Seed wt./pod (gm)*	*Vegetative wt (g/plant)*	*Grain yield (kg/ha)*
Year	1987	20.8 c	0.8 c	0.311 c	432.7 d	1,7003 d
	1988	34.8 b	1.2 b	0.315 c	512.0 b	2,033.0 c
	1989	21.9 c	0.3 d	0.432 a	669.0 a	3362.8 a
	1990	43.4 a	1.9 a	0.375 b	462.9 c	2,490.0 b
Water treatment	1	32.1 ab	0.9 ab	0.391 a	510.8 a	25345 a
	2	25.8 b	0.8 b	0.374 ab	510.0 a	2,295.9 ab
	3	34.5 a	1.1 ab	0.346 ab	524.6 a	2,528.8 a
	4	30.0 ab	1.4 a	0.322 b	5205 a	2,383.4 ab
	5	333 a	1.1 ab	0.364 ab	519.0 a	2,431.8 ab
	6	29.1 ab	1.3 ab	0.343 ab	516.6 a	2,296.7 ab
	7	25.8 b	0.9 ab	0.376 ab	541.6 a	2,458.9 ab
	8	28.6 ab	1.1 ab	0.359 ab	513.1 a	2,239.6 b
	9	30.0 ab	0.9 ab	0.357 ab	524.2 a	2,410.5 ab
	10	33.0 a	0.9 ab	0.347 ab	511.0 a	2,382.5 ab

Notes: Means with the same letter are not significantly different.
Differences between years were determined using the Duncan multiple range test with $\alpha = 0.05$.
Precipitation treatments:
1. Natural rainfall.
2. Increase all daily rains 10 percent
3 . Increase all daily rains 25 percent
4. Increase all daily rains 40 percent.
5. Increase all daily rains of 2.54 mm to 25.4 mm by 10 percent (moderate rain).
6. Increase all daily rains of 2.54 mm to 25.4 mm by 25 percent (moderate rain).
7. Increase all daily rains of 2.54 mm to 25.4 mm by 40 percent (moderate rain).
8. Increase all daily rains above 25.4 mm by 10 percent (heavy rain).
9. Increase all daily rains above 25.4 mm by 40 percent (heavy rain).
10. Increase all daily rains less than 254 mm by 40 percent (light rain).

relationship in the first two stages may represent one temperature response, while that in the last growth stage was separate.

Vegetative mass also decreased with increasing maximum temperature (figure 23a) and nonoptimal minimum temperatures during stage 1, planting to first unifoliate (figure 23b), and stage 4, first flower to maturity (figure 23c). Almost identical relationships were observed with total grain yield and temperature (figure 24).

Figures 22, 23, and 24 indicate the high dependence of final soybean yield on the yield components of vegetative mass and mass of seeds per pod. Final yield did not appear to depend on the number of pods per plant in this four-year experiment.

Combined Data

The three corn experiments and the two soybean experiments were conducted as separate tests relative to the water treatments. However, they experienced the same temperature, humidity, and solar radiation regimes within each year. The mobile shelter and open-area experiments also received identical cultural practices each year, except where noted above.

The crops in the mobile shelter and planting date experiments experienced normal summer precipitation ranges in each of the five years. But the temperature and relative humidity regimes were different each year. For example, in 1988 and 1991, the "wet year" treatments in the mobile shelter experienced "dry year" atmospheric conditions; the "dry year" treatments in 1989 and 1990 experienced "wet year" atmospheric conditions.

The open-area experiments received natural rainfall as well as supplemental water applications to simulate the increased rainfall that might occur with an effective cloud seeding program or with irrigation. Transferring the knowledge gained in the open-area experiment to the farm would be easy. However, the range of rainfall was limited in each of the years and was not as complete as the treatments used in the mobile shelter. Therefore, the data were combined to 1) see if they could be assumed to be from the same mean population, and 2) if more could be learned from the combined data sets.

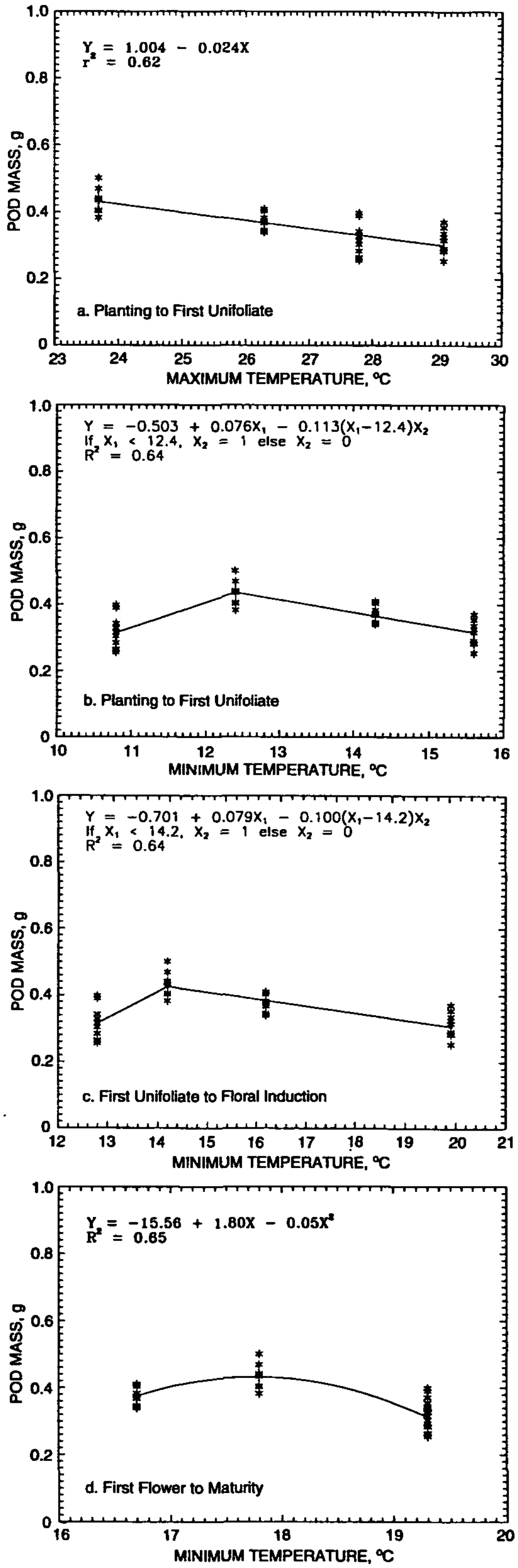

Figure 22. Soybean mass per pod as a response to maximum and minimum temperatures during stage 1 (a,b) and minimum temperature during stages 2 and 4 (c.d), open-area study

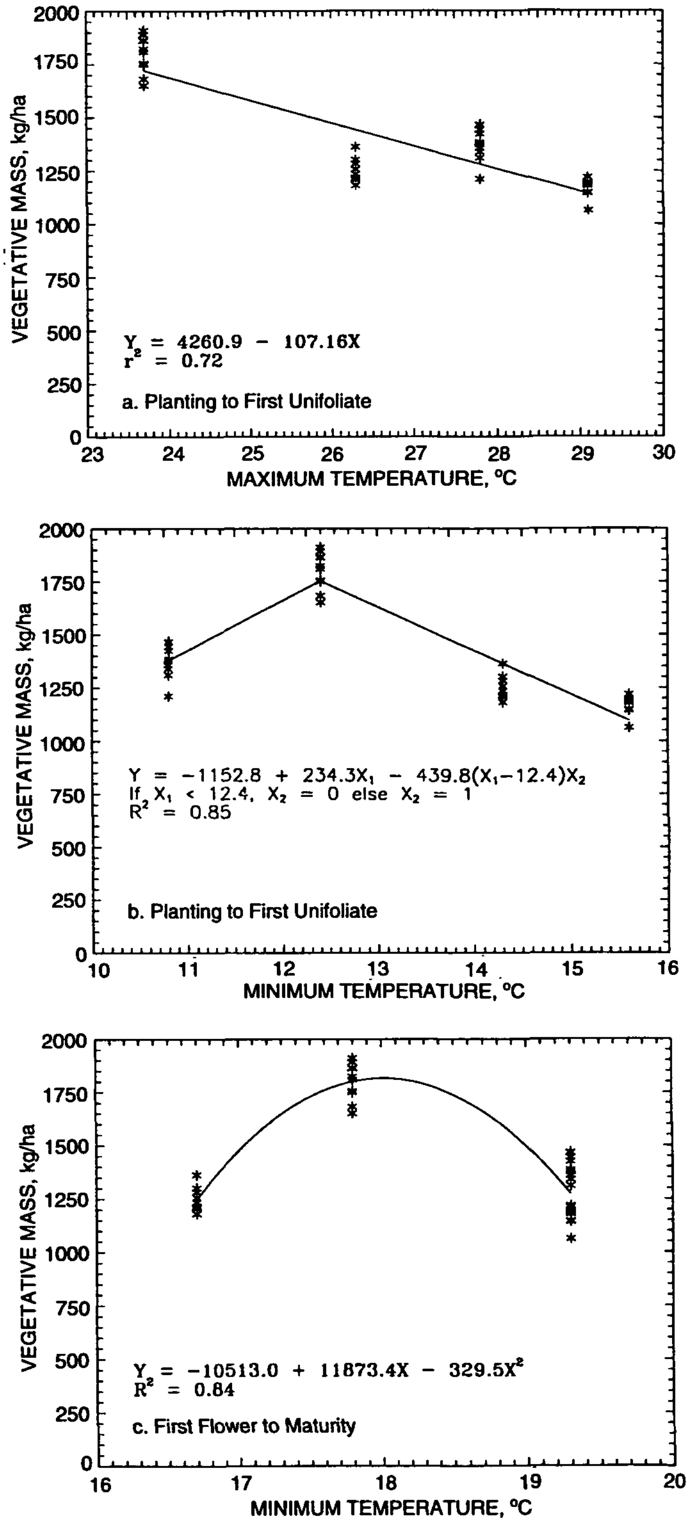

Figure 23. Soybean vegetative mass as a response to maximum temperature during stage 1 (a) and minimum temperature during stages 2 and 4 (b.c). open-area study

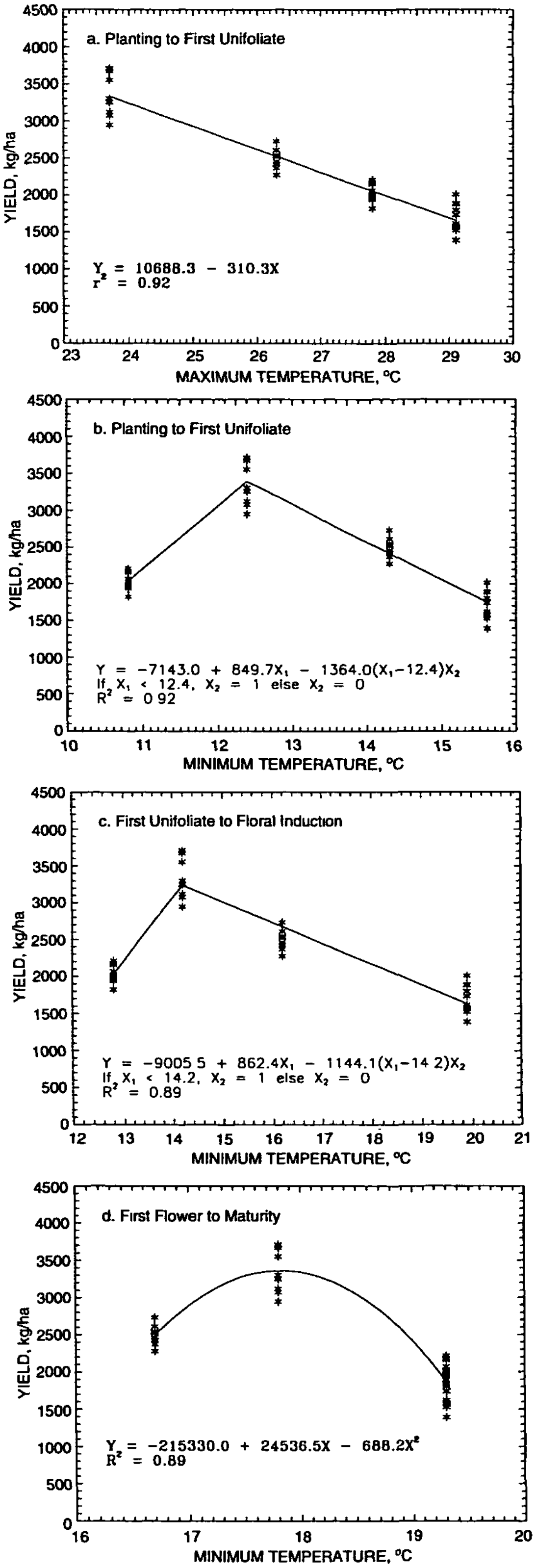

Figure 24. Soybean yield as a response to maximum temperature during stage 1 (a) and minimum temperature during stages 1, 2, and 4 (b, c, and d), open-area study

Corn Experiments

Before the corn data could be pooled to examine total yield and component responses to rainfall and temperature, it was necessary to ensure that the data were from the same population. Figure 25 shows the yield of the three individual experiments plus all the pooled yields compared with rainfall. The open-area values (figure 25c) are not as scattered as those of the mobile shelter and planting date studies. But when all are combined (figure 25d), the open-area yields cannot be distinguished from the mobile shelter and planting date yields. Plots of the yield components (not shown) gave results similar to these. The conclusion was, therefore, that the data from the three experiments were from the same population.

Statistical assessment of the yields showed that they were not significantly different, as determined by a student *t*-test using a pooled sum of squares. The pooled sum of squares was necessary because a Bartlett test (Neter and Wasserman, 1974) showed the variances from the three populations to be unequal.

To examine temperature responses, the data could be pooled without concerns about their independence because all three experiments were exposed to the same temperatures each year. Plotsof the effect of minimum temperature on grain yield show that all three experiments responded similarly to minimum temperature during stage 1, planting to tassel initiation (figure 26a). The scatter in the data points at each of the temperatures sampled is a combination of the rain treatment effects and random error containing other variables that were not controlled or measured. To determine the true response below 13°C, additional experiments are needed. Experiments are also needed to decouple the maximum and minimum temperatures, because the response to maximum temperature below 29°C (figure 26b) was similar to the minimum temperature response above 14°C.

Other curvilinear responses from the individual corn experiments were less clear when the data were pooled. Therefore, any conclusions as to the importance of temperature responses in the individual experiments must be made with caution.

Soybean Experiments

When the data from the two soybean experiments were combined, different relationships were observed in the mobile shelter and the open-area experiments. The results indicated that the soybeans in the open area either responded differently to the environment and the treatments than those in the mobile shelter, or that an uncontrolled variable or event was not accounted for. One possible explanation is that the soybeans in the mobile shelter were grown on the same plots each year (a monoculture), whereas the open-area soybean plots were rotated between corn and soybeans. The monoculture situation may have allowed soilborne diseases to build up, which could change the crop's response to temperature and added water.

When the open-area (figure 27b) and the mobile shelter soybean yields (figure 27a) are compared for response to the

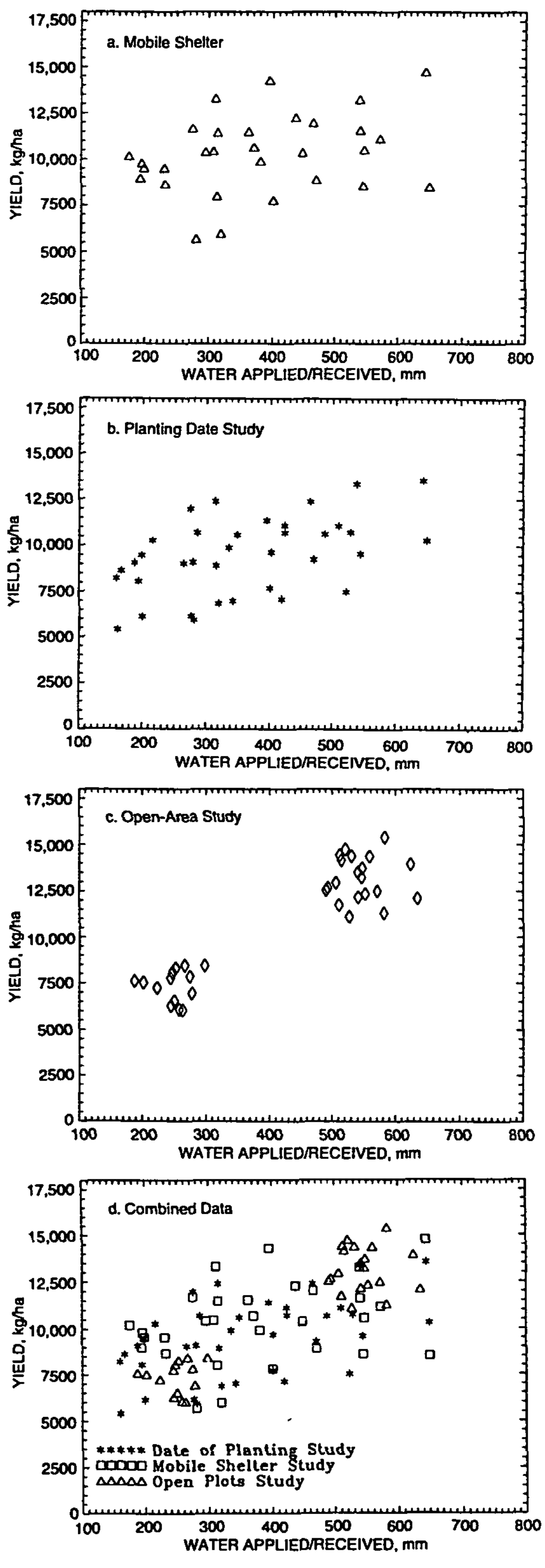

Figure 25. Corn yields as a response to total water received from planting to maturity, mobile shelter study (a), planting date study (b), open-area study (c), and for all studies combined (d)

water received throughout the growing season, the open-area plots showed no clear response. Further, the open-area yields were much more variable than those in the mobile shelter.

The only soybean yield component that showed any consistency between the two experiments was the response of the number of pods with and without beans to maximum temperature during stage 1, planting to first unifoliate. The number of pods with and without beans peaked at an average maxim um temperature of 24.5°C. Below 24.5°C, the number of pods with and without beans decreased more rapidly than it did above 24.5°C.

Model Comparisons

A major reason for conducting the field experiments was to determine how corn and soybeans would respond to increased rainfall due to weather modification. The field studies were also used to assess some models used to simulate the effects of weather modification on final crop yields. Changnon

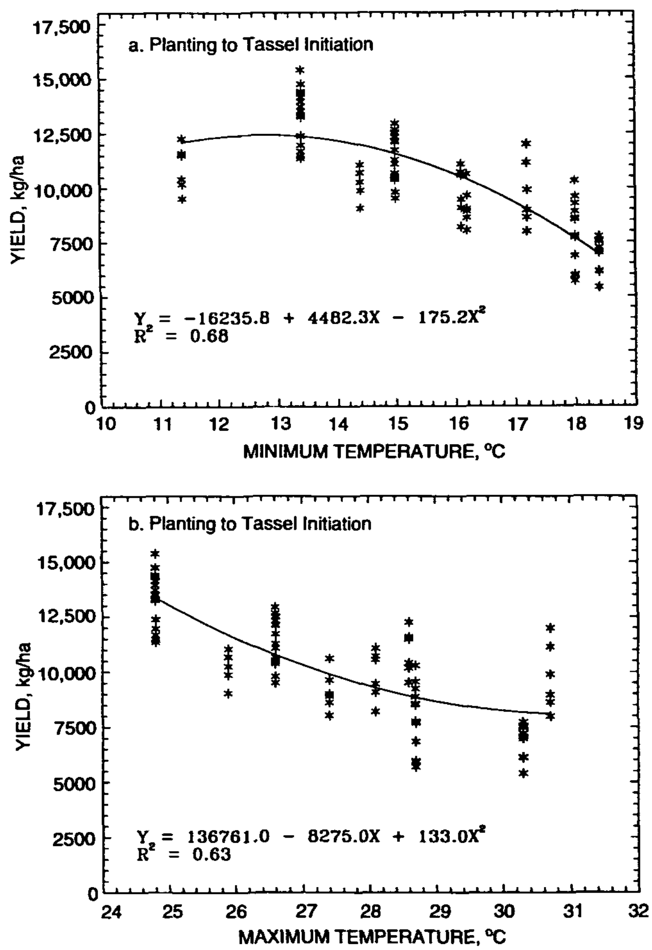

Figure 26. Corn yield as a response to minimum and maximum temperatures (a and b) during stage 1 for all studies combined

et al. (1989) showed that when applied to the first two years of the field experiment, a model developed by Offutt et al. (1987) over-predicted the effects of additional rainfall on corn during wet and dry years and under-predicted it in average years. The predictions for soybeans were relatively good in 1987, but the model under-predicted the response of soybeans to additional rainfall in 1988, a hot dry summer.

Statistical regression models such as Offutt's are limited in their ability to simulate the effects of individual rainfall events. Therefore, the CERES-Maize (Jones and Kiniry, 1986) and SOYGRO models (Wilkerson et al., 1983) were run using the five full years of data on daily air temperature, solar radiation, evapotranspiration, and rainfall treatments applied to the five experiments to determine how well these models would simulate the field results.

A comparison of the corn model results to the observed yield, number of kernels per ear, and kernel mass (figure 28) shows that the model failed to depict the effects of the rainfall treatments accurately. The model limited kernel mass at too

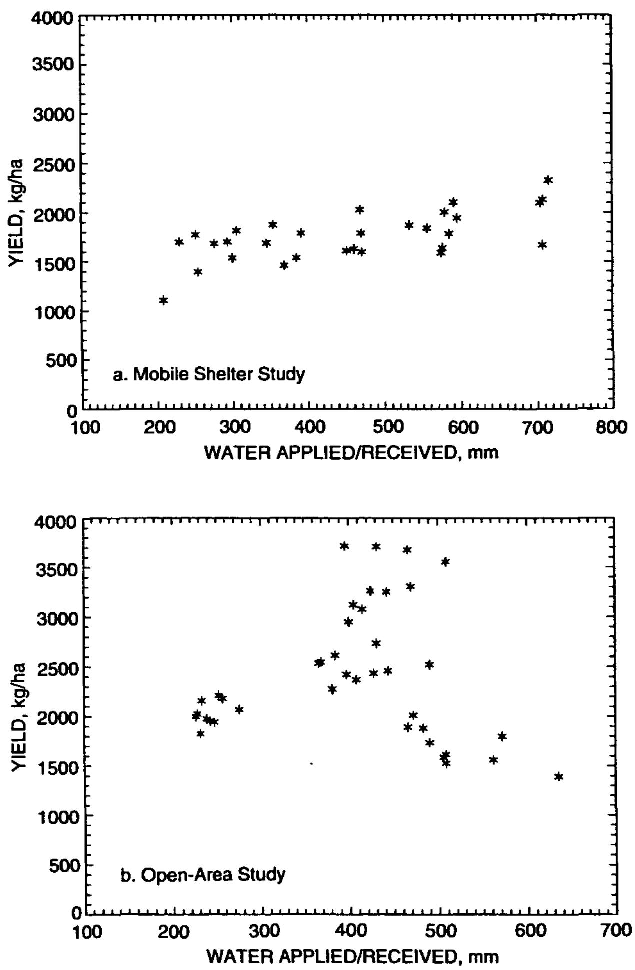

Figure 27. Soybean yield response to total water received from planting to maturity, mobile shelter study (a) and open-area study (b)

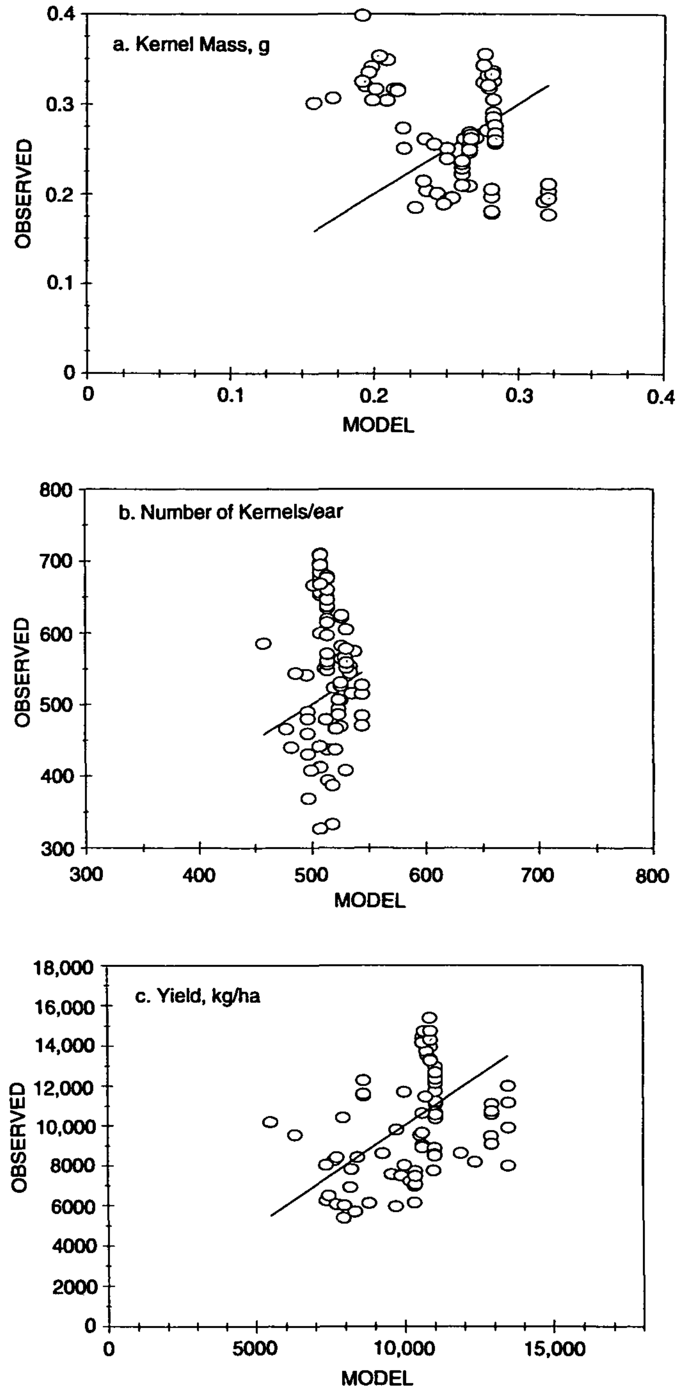

Figure 28. Comparison of modeled and observed kernel mass (a), number of kernels per ear (b), and yield (c)

low a level (figure 28a), although the smallest simulated kernels were approximately the same mass as the smallest observed kernels. Unfortunately, there was not a one-to-one correspondence in kernel size.

The model also failed to simulate the correct number of kernels per ear. In fairness to the model, it does not account for barren or nubbin ears, while they are included in the computation of the mean kernels per ear in the observed data. The nubbin ears tend to increase the number of kernels per ear because all the kernels are assumed to be in one row. Recall that the observed kernels per ear were computed by multiplying the number of rows per ear by the number of kernels per row. However, this was a problem in only a small number of cases. The model, in general, limited the range of the ear size more than what was observed (figure 28b).

Perhaps the best corn simulation result was that of final yield (figure 28c), although it failed to be in close agreement. The range of simulated corn yields was similar to those observed in the field plots, but there was no one-to-one correspondence. The vertical line of data points (figure 28c) indicates the inability of the CERES-Maize model to assess the yield effects of the small changes in rainfall on the open-area plots.

The SOYGRO model performed only slightly better in simulating the soybean yields (figure 29). The simulated range of yields was about the same as the observed yields, although the soybean model also lacked a good one-to-one correspondence. As with the corn model, this model was unable to simulate yield differences due to the rainfall additions on the open-area plots.

Failure of the models to simulate the field plot results illustrates the importance of conducting crop impact research at the field level, as in this experiment. The difficulty with field research, however, is the uncertainty in extending observations from one location to another, where soils and weather may be different. This in fact was the reason the crop-weather models performed so poorly for this application. The models were developed using data from locations throughout the United States and were designed to simulate larger area yield responses. Therefore, applying the models to plot yields was like applying the information obtained from this experiment in east-central Illinois to a vast area in western Nebraska. The lesson to be learned is the need for caution in interpreting model results and applying field plot data to remote locations.

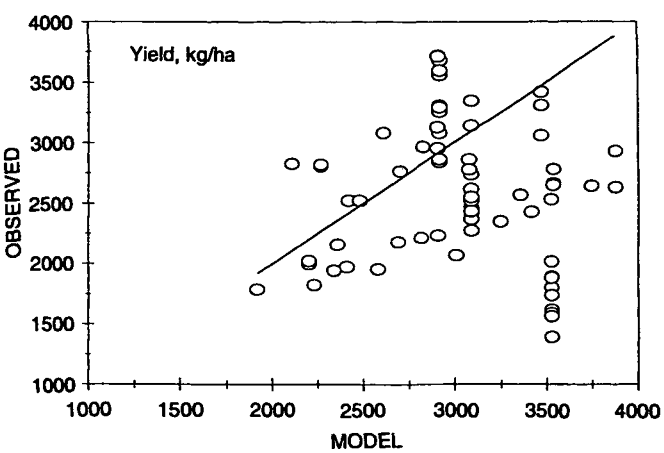

Figure 29. Comparison of modeled and observed soybean yields

Summary and Discussion

Determining the potential benefits of weather modification for agricultural production has been an ongoing concern of Illinois State Water Survey weather modification research. Past crop-weather modeling studies conducted to estimate effects left many unanswered questions because of the limitations of the models. Therefore, a five-year field experiment was undertaken to study crop responses to additional rainfall that mimicked the additional water that might be gained from weather modification. The field studies have the advantage over the regression models in that the growing crop experiences all the weather conditions of the season as individual events, not just the mean weather of a given period. The models have the advantage in being able to evaluate general effects over larger areas.

Two types of field studies were undertaken: 1) plots covered by mobile rain shelters, and 2) plots in the natural environment. Water was added to both types of plots on different schedules. The mobile rain shelters kept all natural rainfall off the plots, and water was applied in a sequence typical of normal dry, average, and wet summers in east-central Illinois. Rainfall treatments of 25 percent more rain were added to each rain event in the typical summers. The open-area plots received natural rainfall and additional water applications after each natural rain. The amounts applied represented increases comparable to what might be expected with an effective weather modification capability. Five years of data were collected to provide a sampling of the different atmospheric conditions that might exist over east-central Illinois.

As expected, results of the field plot studies indicate that yields increase with increasing rainfall throughout the summer. However, the small rainfall increases applied after the individual storms produced differing responses, depending on the prevailing climatic conditions. The data were analyzed by segmenting the rainfall according to the different corn and soybean growth stages to identify the importance of the timing of the rainfall increases. Unfortunately, no strong relationships were found because the rainfall differed within each growth stage among the years. To fully understand the importance of rainfall timing in a field situation, additional experiments will have to be designed for this specific purpose.

Agronomically, the most exciting observation was the reduction of corn yields as the temperature increased during stage 1, the first 20 to 30 days of growth, from planting to tassel initiation. This finding has implications for the possible effects of a wanning climate on Illinois corn production. The information may be used to fine-tune the time of planting for higher yields. Because of the limited number of years and observations relative to this finding, additional experiments are needed to verify this temperature relationship and explain the physiological relationship between higher corn yields and cooler temperatures during the early growth of the corn crop.

IMPLICATIONS FOR WEATHER MODIFICATION

Effects of Rainfall and Temperature on Yields

The effects of the rainfall treatments on crop yields were assessed in two ways. One was based on a comparison of the average yields obtained for each of the ten water treatments. The second approach sought to measure the consistency of each treatment's performance; that is, its yield level in each year relative to other years. This was done because a given treatment would provide good yields in certain years, but relatively poor yields in others, depending on the weather conditions. As noted previously, the effect of rainfall in an individual summer varies depending upon its level and timing and temperature conditions. The treatments were compared using two rankings: one based on the average yields for the total experimental period, and another derived from individual annual yields.

Corn Results

Table 13 (upper portion) presents the relative ranks of each of the ten treatments used during three years of corn experimentation, 1988-1990. For each treatment, the yields of each year were ranked, and these rank scores were summed to form a three-year sum of ranks. These sums were then ranked, as shown in the last column. For example, the no-increase rainfall

Table 13. Analysis of Annual Corn Yields According to Rain Treatments, Open-Area Plots, 1988-1991

Three-Year Study

Treatment	*Rants* 1988	1989	1990	*Sum of ranks*	*Rank of sums*
1	8	3	3	14	3-4
2	9	9	10	28	10
3	6	1	9	16	5-6
4	2	7	7	16	5-6
5	5	4	8	17	7-8
6	10	5	6	21	9
7	3	10	4	17	7-8
8	7	2	1	10	1
9	1	8	5	14	3-4
10	4	6	2	12	2

Four-Year Study

Treatment	*Ranks* 1988	1989	1990	1991	*Sum of Ranks*
1	3	2	1	2	9
2	4	4	4	3	16
3	2	1	3	4	7
4	1	3	2	1	8

Notes: Precipitation treatments:

1. Natural rainfall.
2. Increase all daily tains 10 percent
3. Increase all daily rains 25 percent.
4. Increase all daily rains 40 percent.
5. Increase all daily rains of 2.54 mm to 25.4 mm by 10 percent (moderate rain).
6. Increase all daily rains of 2.54 mm to 25.4 mm by 25 percent (moderate rain).
7. Increase all daily rains of 2.54 mm to 25.4 mm by 40 percent (moderate rain).
8. Increase all daily rains above 25.4 mm by 10 percent (heavy rain).
9. Increase all daily rains above 25.4 mm by 40 percent (heavy rain).
10. Increase all daily rains less than 254 mm by 40 percent (light rain).

treatment (number 1) produced a 1988 yield that ranked eighth highest among the ten treatments. Then, the treatment produced a yield that ranked third best in 1989 and in 1990. The rank sum score of these was 14. Treatment 8 (10 percent increases to heavy rains >25.4 mm) had a rank sum score of 10, the best three-year performance.

The lower portion of table 13 presents the annual ranks for the four treatments applied over the 1988-1991 four-year period. Their sum of ranks reveals that the 10 percent increase to all rains (treatment 2) was the worst, and that treatment 4 (40 percent increases to all rains) was the best, but just slightly better than treatments 1 (natural rainfall) and 3 (25 percent increases to all rains). Note also that the best treatment shifted considerably between years: treatment 4 (40 percent increases) in 1988 and 1991, treatment 3 (25 percent increases) in 1989, and treatment 1 (no rain increase) in 1990.

The three-year individual annual yield ranks were reviewed for relative consistency. One of the two most effective rain treatments, number 10, showed the greatest consistency from year to year. The best performing treatment, number 8, achieved the lowest rank sum score of 10 and was excellent in two years (1989 and 1990) but poor (ranked 7) in 1988, the extremely hot and dry summer.

The rank sum scores were also used to identify the treatments that gave poor corn yields. Treatment 2 (10 percent increases to all rains) was the worst with a score of 28, followed by treatment 6 (25 percent increases to moderate rains) with a score of 21. Importantly, treatments 2 and 6 ranked consistently low in all three years.

Table A32 presents the three-year (1988-1990) and four-year (1988-1991) average corn yields for the treatments, ranked from high to low. The greatest three-year yield increases — increases ≥ 400 kg/ha more than was produced by natural rain (treatment 1) — were produced by treatments 10, 9, 4, and 5. Treatments 3, 7, and 8 also increased average yields above the natural rainfall for 1988-1990, while treatments 2 and 6 reduced yields much below those resulting from natural rainfall.

Of the nine rainfall-added treatments, treatment 10 (40 percent added to light rains) was the best for 1988-1990 in terms of average yields and consistency of annual yields. Treatments 2 (10 percent added to all rains) and 6 (25 percent added to moderate rains) decreased yields and performance in all years. The four-year assessment of treatments 1-4, based on consistency and average yield (table 13), revealed that treatment 4 (40 percent increases to all rains) was best for corn grown during 1988-1991. Treatment 2 (10 percent increases to all rains) was the worst.

Soybean Results

Table 14 ranks the annual soybean yields for 1987-1990. The yields with treatment 1 (no increase to actual rainfall) ranked second best in 1987, sixth highest in 1988, first in 1989, and fourth in 1990, for a sum score of 13. The ranks of the sums (last column) reveal that treatment 1 (no increase) was the best, treatment 7 (40 percent more water on moderate rain days) was second best, and treatment 3 (25 percent increase to all rain) was a close third. Treatment 3 was consistently good in all years, while treatments 1, 7, and 5 showed greater variation between years: each had two high-ranking yield years and two moderate to low-ranking yield years. The soybean yields produced by treatments 2, 6, and 8 all had much higher rank scores, 30 to 33, and led to poor yields in all four years.

The annual soybean yield responses (figure 30) were plotted with respect to total summer rainfall. The annual yields occurred in distinct groups and tended to increase as total summer rainfall increased to about 420 mm. Thereafter, yields decreased as conditions became too wet The wet and cool conditions of 1990 were clearly not as good for soybeans as the near-average weather conditions in 1989. The relative shifting of treatments within and between years is also informative. Note how treatment 1 (no added rain) was good in 1987 and 1989 (years with ample summer rains) and poor in 1988 (a very dry year).

Table A33 presents the rank order of the average four-year soybean yields resulting from the ten treatments. Treatment 1 (no rain addition) was the best with an average of 2,535 kg/ha. However, treatments 3 and 7 had averages very close to the top value, with differences less than 100 kg/ha. Treatments 2, 6, and 8 produced the lowest average yield responses, defined as those >200 kg/ha below the best.

In summary, the best performing treatments for soybean yields during 1987-1990 were treatment 1 (no increase), treatment 7 (40 percent added to moderate rains), and treatment 3 (25 percent added to all rainfalls). All produced high average yields, and the annual yields were consistently high in all four years. Treatment 7 rated best in 1988 and 1990. Treatment 3 was good in all years except 1990. The treatments rated worst for soybean yields were treatment 8 (10 percent added to heavy rains), treatment 4 (40 percent added to all rains), and treatment 6 (25 percent added to moderate rains). The different annual yield outcomes from any one treatment indicate the sensitivity that would have to be employed in a cloud seeding project: more rain could either hurt or help soybean yields, depending on how much occurs naturally.

Assessment of Treatments to Each Crop

The corn yield-rainfall results revealed that treatments 8 and 10 achieved the most consistent, all-year benefits based on the 1988-1990 period. They were closely followed by treatment 9. Analysis of average yields for the three-year period supported these outcomes: overall, treatments 10 (40 percent added to light rains) and 9 (40 percent added to heavy rains) were the best. Treatments 2 (10 percent added to all rains) and 6 (25

Table 14. Analysis of Annual Soybean Yields According to Rain Treatments, Open-Area Plots, 1987-1990

	Rank					
Treatment	*1987*	*1988*	*1989*	*1990*	*Sum of ranks*	*Rank of sums*
1	2	6	1	4	13	1
2	9	7	6	8	30	8-9
3	4	2	3	6	15	3
4	10	4	4	5	23	6
5	3	3	9	2	17	4
6	6	8	7	9	30	8-9
7	7	1	5	1	14	2
8	5	10	8	10	33	10
9	8	9	2	7	26	7
10	1	5	10	3	19	5

Notes: Precipitation treatments:

1. Natural rainfall.
2. Increase all daily rains 10 percent
3. Increase all daily rains 25 percent
4. Increase all daily rains 40 percent
5. Increase all daily rains of 2.54 mm to 25.4 mm by 10 percent (moderate rain).
6. Increase all daily rains of 2.54 mm to 25.4 mm by 25 percent (moderate rain).
7. Increase all daily rains of 2.54 mm to 25.4 mm by 40 percent (moderate rain).
8. Increase all daily rains above 25.4 mm by 10 percent (heavy rain).
9. Increase all daily rains above 25.4 mm by 40 percent (heavy rain).
10. Increase all daily rains less man 2.54 mm by 40 percent (light rain).

percent added to moderate rains) were undesirable for enhancing corn yields in all years. The four-year tests of four treatments indicated that treatment 4 (40 percent increases to all rains) was the best

Interpretation of these outcomes reveals that water added to increase corn yields on rain days was best when more water (40 percent) was applied to any natural daily rainfall. Corn yields, on the average, did not benefit by applying 25 percent increases to moderate rainfalls or 10 percent to all rains.

Analysis of the soybean responses revealed that for most years, the best treatments were 1 (no rain increase), 7 (40 percent added to moderate rains), and 3 (25 percent added to all rains). The worst four-year treatments for soybeans were 2, 6, and 8. These treatments amounted to adding too much water on moderate to heavy rain days, or too little water. In the extremely dry year of 1988, most rain increases of 25 to 40 percent were beneficial to soybeans.

Assessment of Treatments Based on Joint Consideration of Both Crops

For analyzing summer rainfall modification or possible impacts of climate change the rain-yield findings must include an assessment of the crops' joint responses to changed rainfall. The crops are grown throughout the Corn Belt, and most farms grow both. Thus, the rain treatments that produced relatively good yields for both crops and those rated as relatively bad for both crops were determined for a regional perspective.

The performance of the ten treatments was classed, based on their rank sums and on the rank of their average yields, from high to low for both corn and soybeans. The combined values, shown

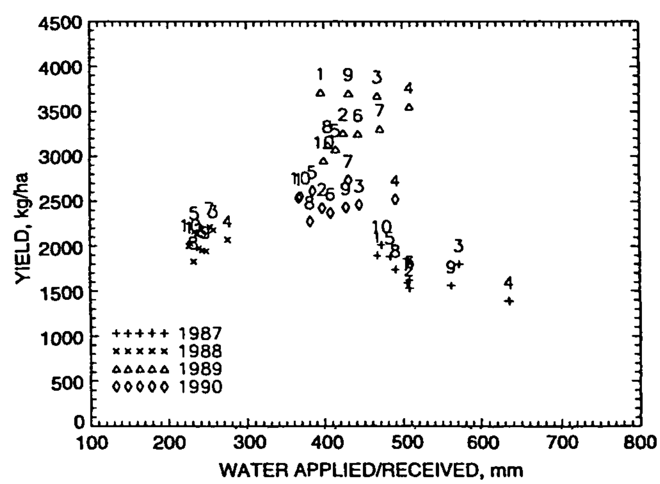

Figure 30. Soybean yield as a response to total water received from planting to maturity, open-area experiment

in table 15, reveal mixed outcomes for most treatments. That is, most treatments good for one crop were not good for the other. Note how treatment 7 was good for soybeans but bad for corn, and how treatment 8 was good for corn, but bad for soybeans. The only relatively good treatments for both crops were treatments 10 and 4. Treatments 2 and 6 were bad for both crops.

The four best and four worst treatments for both crops, based on their four-year rank scores and the ranks of average yields, are listed in table 16. Also shown are the four best and worst treatments in the dry, normal, and wet years. Treatments 1, 7, and 10 were good for both crops in wet summers (1987 and 1990); treatments 4 and 5 were good for both crops in the dry summer (1988); and treatments 1 and 3 were good in the near-average summer (1989). These shifts between seasons reinforce the need to identify the correct treatment for all years, assuming the decision has to be made at the start of the summer. The assessment of the worst treatments clearly establishes that treatments 2 (10 percent added to all rains) and 6 (25 percent added to moderate rains) would be undesirable in the types of summer weather conditions that occurred during 1987-1991.

It was informative to compare the average magnitude of the yield increases with 25 percent rain increases in this experiment with results found elsewhere. Average summer rain increases across a two-county area downwind of St. Louis were calculated to be 10 to 25 percent over two decades (Changnon et al., 1981). An analysis of crop yields in this rain-affected area revealed an average increase of 7.5 percent in annual corn yields and 4.1 percent in soybean yields. Both shifts were found to be significant at the 5 percent level (Changnon et al., 1981). The addition of 10 percent extra rainfall produced a 3.5 percent increase in the 1988-1991 experimental corn yield, and a 1 percent decrease in the average 1987-1990 soybean yield. Neither corn nor soybeans responded to the increased rainfall in the plot experiment as in the Changnon et al. study (1981). This may result from different conditions in the sampled years.

Integrating Yield-Weather Results with Other Factors

The open-area studies measured yield changes under natural rain conditions, and the results offer the best data for assessing all the effects of cloud seeding. These results were integrated and interpreted with other factors affecting the use of weather modification in Illinois and most areas with similar

Table 15. Assessment of Rain Treatments and Crop Yields, Open-Area Plots

	Treatments ranked by each crop	
Rank	*Com*	*Soybeans*
l(best)	10	1
2	9	7
3	8	3
4	4	5
5	3	4
6	1	10
7	5	9
8	7	6
9	6	2
10 (worst)	2	8

Notes: Precipitation treatments:

1. Natural rainfall.
2. Increase all daily rains 10 percent
3. Increase all daily rains 25 percent
4. Increase all daily rains 40 percent
5. Increase all daily rains of 2.54 mm to 25.4 mm by 10 percent (moderate rain).
6. Increase all daily rains of 2.54 mm to 25.4 mm by 25 percent (moderate rain).
7. Increase all daily rains of 2.54 mm to 25.4 mm by 40 percent (moderate rain).
8. Increase all daily rains above 25.4 mm by 10 percent (heavy rain).
9. Increase all daily rains above 25.4 mm by 40 percent (heavy rain).
10. Increase all daily rains less than 254 mm by 40 percent (light rain).

humid continental climates, deep prairie soils, agricultural practices, and rules relating to the use of cloud seeding.

The factors addressed concern the operational aspects of cloud seeding, such as the ability to seed clouds with aircraft at night and laws restricting seeding during severe storms. They also include integrating the open-area plot yield results, which identified the rain events and increases that would enhance yields, with regional data on rain frequency.

Rainfall enhancement in a humid zone like Illinois is affected by various climatic factors. One of these is the occurrence of too much summer rain, which decreases crop yields in about 15 percent of the summers (Changnon, 1969). Hence, continual year-to-year use of cloud seeding to increase rain would reduce yields in some years, negating the value of rainfall modification in drier years. Furthermore, the open-area plot results found considerable year-to-year variation in the yield responses to most added water treatments. That is, a treatment providing a good response one year often did poorly in the next. These differences related to between-season variations in the timing and amounts of rainfall and to temperatures during June-August. The areal distribution of rainfall amounts across an area with a typical cloud seeding project would also influence the value of the rain enhancement.

Rainfall modification, unlike irrigation, cannot be "turned on and off* at will. Rain enhancement projects are not permanent installations like irrigation facilities. A quality rain modification project requires skilled staffing and facilities (e.g., radars and aircraft) that are installed a few weeks in advance of the operations. Cloud seeding occurs on those days when nature provides appropriate rain conditions, not necessarily when the soil moisture is low and crop stress is high.

These factors were investigated using a hypothetical cloud seeding project in Illinois. The area used to simulate the project was selected according to past research on soils, weather

Table 16. Four Best and Four Worst Rain Treatments According to Annual Yield Consistency, Average Yield, and Performance in Different Years

Best Treatments

Crop	*Annual yield rank score*	*4-year average yield*	*Rank in wet years (1987 and 1990)*	*Rank in near average year (1989)*	*Rank in dry year (1988)*
Corn	8, 10, 9, 1	10, 9, 4, 5	8, 10, 1, 7	3, 8, 1, 5	9, 4, 5, 10
Soybeans	1, 7, 3, 5	1, 3, 7, 5	10, 5, 1, 7	1, 9, 3, 4	7, 3, 5, 4

Worst Treatments

	Annual rank score	*Average yield*	*Wet years*	*Average year*	*Dry year*
Corn	2, 6, 7, 3-4 (tied)	2, 6, 1, 7	2, 3, 5, 4	7, 2, 9, 4	6, 2, 1, 8
Soybeans	8, 2, 6, 7	8, 2, 6, 10	2,6-4-8 (tie)	10, 5, 8, 6	4, 2, 9, 7

Notes: Precipitation treatments:

1. Natural rainfall.
2. Increase all daily rains 10 percent
3. Increase all daily rains 25 percent
4. Increase all daily rains 40 percent
5. Increase all daily rains of 2.54 mm to 25.4 mm by 10 percent (moderate rain).
6. Increase all daily rains of 2.54 mm to 25.4 mm by 25 percent (moderate rain).
7. Increase all daily rains of 2.54 mm to 25.4 mm by 40 percent (moderate rain).
8. Increase all daily rains above 25.4 mm by 10 percent (heavy rain).
9. Increase all daily rains above 25.4 mm by 40 percent (heavy rain).
10. Increase all daily rains less than 2.54 mm by 40 percent (light rain).

conditions, and crop yields (Changnon and Neill, 1967). This research defined a seven-county, 13,000-km^2 region in east-central Illinois, including Urbana and the experimental plots, with highly similar yield-weather relationships. From this regional simulation, the potential costs and direct benefits of a cloud seeding project were estimated over a series of years like 1987-1991. The results were used to assess the value of rain enhancement to Illinois and to identify needs for future cloud seeding research.

The assessment of summer rain days suitable for modification was based on historical daily rain data for Champaign-Urbana for 1903 through 1991. The resulting frequency distribution for the area in three rain classes is shown in table 17. The frequency distribution was computed using 1951-1980 daily data from 14 weather stations throughout the area. The climatic analyses were based on the three classes of daily rainfall: light (0.25 to *25* mm), moderate (2.5 to 25.4 mm), and heavy (>25.4 mm). To assess operational requirements for aircraft on rain days in the area, area radar echo data were analyzed for three summers (Dzurisin, 1983).

Factors Affecting the Use of Cloud Seeding for Rain Enhancement

Considerations from Crop Yield Results

The three levels of summer rainfall increases tested, 10, 25, and 40 percent, were assessed. These bracket the range of capabilities believed possible through weather modification endeavors (WMAB, 1978). The outcomes provide guidance for scientific cloud seeding experiments (Changnon et al., 1991).

The three treatments involving 10 percent rain increases generally were not beneficial to yields. The 10 percent increase to all rains (treatment 2) was rated the worst of all ten treatments for each crop. Treatment 8 (10 percent added to heavy rains) was satisfactory for corn yields, but poor for soybean yields. Treatment 9 (40 percent added to heavy rains) was also good for corn but not for soybeans. Since 39 percent of the Illinois acreage is planted in soybeans and 48 percent in corn, these would not be desirable regional treatments. A weather modification capability that only achieved 10 percent summer rainfall increases area-wide could not be recommended, based on the five years sampled.

The assessment of 25 percent rainfall increases was based on two treatments, plus a synthesis of the value of 25 percent increases to heavy rains. Treatment 6 (25 percent increase to moderate rains) was overall one of the worst water treatments for both crops, and resulted in four-year average soybean yields 238 kg/ha below those with natural rainfall. Treatment 3 (25 percent increases to all rains) rated well for soybean yields, which were equivalent to those with natural rainfall, and for corn yields during 1988-1991.

Data from treatments 8 and 9, 10 and 40 percent increases on heavy rain days, respectively, were used to interpolate results for a 25 percent increase to heavy rains. Interpolation indicated that a 25 percent increase to heavy rain days would rate in the "good" category (estimated as rank 5 on a scale of 1 to 10). Soybean yields were only marginally helped by 25 percent rain increases applied on all rain days, and they were hurt with 25 percent increases on moderate rain days. Corn yields dropped with 25 percent increases on days of moderate rains, and rose slightly with 25 percent increases on all days.

Table 17. Frequency of Summer (June-August) Rain Days in Three Class Intervals, Expressed as a Percent of the 1903-1991 Total in Each Class at Champaign-Urbana, IL

No. of Days	*Light rains (0.25-2.5mm)*	*Moderate Rains (2.6-25.4 mm)*	*Heavy rains (>25.4 mm)*
0	0	0	10%
1	0	0	16%
2	0	0	23%
3 to 4	6%	0	40%
5 to 6	7%	6%	9%
7 to 8	26%	6%	2%
9 to 10	27%	8%	0
11 to 12	13%	22%	0
13 to 14	8%	16%	0
15 to 16	12%	17%	0
17 to 18	1%	20%	0
19 to 20	0	5%	0
Average number	10	13	3

Analysis of the 40 percent rainfall increases was based on four treatments that embraced a wide range of possible rainfall conditions. Forty percent rain increases produced generally positive yield responses: on days with light rain (≤2.5 mm) or heavy rain (>25.4 mm) they had marginal value for soybeans, but resulted in high average corn yields. Increases of 40 percent on all rain days were moderately good for both crops (see table 15, treatment 4). It is also important to note that 40 percent increases were very beneficial to corn and soybean yields during the extremely hot and dry summers of 1988 and 1991.

The 1987-1991 open-area yield results were used to assess rainfall modification activities and to classify the daily rainfall amounts according to three categories: light (0.25 to 2.5 mm), moderate (2.5 to 25.4 mm), and heavy (>25.4 mm). Yield results had shown little value to increasing light rains, unless increases of 40 percent or more could be accomplished. Increases of 25 percent on days of moderate rainfall were not useful to crops, but 25 percent added to all rain days was marginally beneficial to both crops. Increases of 40 percent on moderate rain days increased soybean yields. Increases on heavy rain days produced very mixed outcomes. Small increases, 10 percent to heavy rain days, benefited corn, but not soybeans; likewise, 40 percent increases on heavy rain days were helpful to corn but of little value to soybeans. Interpolation of the effect of 25 percent increases to heavy rains indicated that this level of increase would be marginally useful to both crops.

Results for each crop, while limited by the four-year sample size, demonstrated that 40 percent increases on moderate or heavy rain days were the best choice for enhancing yields of both crops in the deep prairie soils of Illinois on a multiyear basis. Of course, this choice is based on a lack of any predictive skills for summer rainfall, including its timing and total amount If one knew in advance that a given summer would be hot and dry, then the results indicate that a 40 percent increase to all rain events is easily the best choice. However, such conditions occur, over a long period, only 14 percent of the time (Changnon, 1969), and the open-area plotresults suggested that a 40 percent increase is not a good treatment in wet summers, which occur about 23 percent of the time (June-August).

Nocturnal Rainfall Limitations

Another climatic factor that affects cloud seeding opportunities and the potential for rainfall increases is the incidence of precipitation at night. On the average, 46 percent of all summer precipitation in Illinois occurs during the nocturnal hours of 2000 to 0600 LST (Changnon and Huff, 1980). Current seeding technologies involve aircraft and depend upon visual observations of the clouds aloft, along with other in-cloud aircraft measurements. Obviously, clouds cannot be observed at night Thus, candidate rain events occurring during the nocturnal hours cannot be considered as potential seedable rain conditions.

Relevant Climatic Factors

Further interpretation of the rain-crop yield results involved consideration of the frequencies of rain days during various intervals during the summer. The relevant average rainfall conditions during June-August include the frequency of rain days and the amounts of rain at a point (table 1) and over an area.

The ≤2.5-mm class of rainfall at a point averages 10 days during the 92-day summer, and these produce, on the average, a combined total of 17.8 mm of rainfall. The average occurrence of the second rain class considered, 2.6 to 25.4 mm per day, is 13 days. These days produce a combined total 137.0 mm of rain on the average. The third class was >25.4 mm, and rain days at this level occur, on the average, three times per summer at a point. These three events typically produce 127.2 mm of the total average summer rainfall. The long-term (1903-1991) summer total average values are 26 rain days producing 282 mm of rain.

Assessment of the crop yield effects-from a rain enhancement project, which is a regional endeavor, must also incorporate the regional climatic conditions, in this case those covering the 13,000-km^2 area in east-central Illinois used for the simulated cloud seeding project. This area generally experiences rains producing point amounts in the moderate range on 31 days each summer (June-August), and an average of 11 days with heavy rains (>25.4 mm) at one or more points.

The areal extent of rainfall is another relevant climatic variable useful for assessing regional yield effects. The areal distribution of heavy rains, in which one or more points in the area experience >25.4 mm, is as follows: 50 percent of these events produce >25.4 mm over 10 percent or less of the simulated project area; 87percentproduce>25.4 mm over only 30 percent of the area; and in only 6 percent does heavy rain extend over at least 50 percent of the project area. A similar analysis was pursued for the areal extent of moderate rainfall, from 2.5 to 25.4 mm, when that amount occurs at one or more points. The areal distribution results showed that rains of >2.5 mm covered 75 percent or less of the project area on 8 days, 50 percent or less of the area on 16 days (52 percent); and less than 25 percent of the area on 23 days (74 percent). Since increases to rains ≤2.5 mm produced minimal benefits to crop yields, the areal extent of rainfall less than 2.5 mm on moderate rain days was deemed of no consequence in assessing the regional benefits of cloud seeding.

Effects of Severe Storm Warnings

The rain days in the 13,000-km^2 project area were also assessed for storm warning days. This assessment is essential because clauses in Illinois law restrict weather modification operations when warnings exist (Changnon, 1983a).

The number of severe storm warnings on rain days in the different rain class intervals was calculated for 1986 through 1990. This revealed that 19 percent of all days with measurable daytime rain had warnings, 32 percent of all days with maximum point rains between 2.5 and 25.4 mm had warnings, and 44 percent of all days with >25.4-mm rains had warnings.

Incidence of Seedable Clouds and Related Operational Requirements

Echo-cell (cloud) frequencies were determined based on three years of radar data. This information was needed because the cloud seeding approaches believed to be most effective require aircraft to deliver seeding material at the cloud base and/or inside the growing cells of each cloud. Each individual echo cell (defined by a reflectivity contour of 20 dBz) over the 13,000-km^2 project area was considered a cloud suitable for seeding in this simulation.

Data on 262 lines of echoes occurring in July-August revealed that when lines existed in the project area, two or more lines occurred; the average duration of echoes in the area was 5 hours; the average number of cells at any one time was 24; and the total number of cells per event was between 65 and 97 (Dzurisin, 1983). Data on 155 echo areas, defined as groups of cells not in a linear array, revealed that they lasted 4 to 7 hours in the project area, with an average of 6; that each covered an average of 1,040 km^2; at any one time there were an average of 13 cells; and that 72 percent of the rain periods had three or four echo areas within the region. The total number of cells in the area per event ranged from 31 to 118.

These statistics were used to calculate the number of high-performance aircraft required to seed each cell for 10 minutes. This showed that during days of moderate to heavy rain (lines or echo areas), three to four aircraft would have to be aloft at a time seeding clouds over the project area. To meet the duration demands of the rain periods (given aircraft times aloft), six jet aircraft would have to be available. A prior analysis for hail suppression projects (Changnon and Morgan, 1976) indicated the need for 12 seeding aircraft for a 6,200-km^2 area in Illinois. This number of meteorological seeding aircraft, ground radar, and the operational support staff represent a project expenditure of approximately $1 million per summer.

Examples of Integrating the Rain Modification Factors

Estimates of the regional crop yield outcomes were based on integrating all the rain modification factors with several different rainfall treatments. From these calculations came estimates of the direct monetary gains and losses. These financial assessments did not attempt to address the more complex secondary economic effects, such as those relating to potential shifts in the interannual variability of crop yields (Changnon, 1983b).

Rain treatments 9, 3, and 6 were assessed for their regional effects and application over a series of years like those sampled, 1987-1991.

Treatment 9: 40 Percent Increases on Heavy Rain Days

Assessing the regional benefits of increasing the average 11 heavy daily rains in summer by 40 percent (treatment 9) began with adjustments for various limitations. First, 46 percent of the events are nocturnal, so 5 of the 11 days in this category are lost for seeding. Then, 44 percent of the remaining six days are unavailable for seeding because of severe local storm warnings. Hence, only three days with heavy rain during June-August offer opportunities for modification.

Analysis of regional rain distributions indicated that in 90 percent of the cases, average rain amounts of >25.4 mm occurred over 30 percent or less of the total area. Assuming the best average outcome, 30 percent of the 13,000-km^2 area, or 3,900 km^2, would experience a 40 percent increase to heavy rains on each of the three available days per summer (equivalent to treatment 9). These heavier rains could all occur in the same area, but a partly overlapping distribution of areas was found on most such rain days in the 30 summers analyzed. For this analysis, it was assumed that one 30 percent portion of the project area had one day of increased heavy rain, and the other two days had increases over separate nonoverlapping areas (each equivalent to 30 percent of the project area). This optimizes the regional benefits by producing a 40 percent rain increase over 90 percent of the project area.

One day with 40 percent increased rain would result in a corn yield increase of one-third the of 425-kg/ha average increase found in the field test, or 142 kg/ha. Treatment 9 also decreased soybean yields by 124 kg/ha below the natural rain effect. When adjusted by the 33 percent, this value becomes a reduction of 41 kg/ha. Since these one-day increases in rainfall would occur over 90 percent of the project area, this factor was used to calculate the area yield effects. The simulation area comprised 7,280 km^2 of corn and 5,200 km^2 of soybeans. Corn was priced at $2 per 25.5 kg and soybeans at $6 per 27.2 kg, values typical during recent years.

The use of treatment9 with the aforementioned limitations over the types of weather years sampled during 1987-1991 resulted in $8.11 million in annual added income due to increased corn yields. The income loss due to decreased soybean yields in the area would be $4.7 million annually, resulting in a net regional gain of $3.41 million per year. Recall that the annual operational costs for a summer modification project were estimated to be $1 million.

Treatment 3: 25 Percent Ram Increases on all Rain Days

Treatment 3,25 percent rain increases on all rain days, was also assessed. The simulated project area averages 42 rain days per summer. Nineteen of those days are lost for seeding due to nocturnal rains, and five of the remaining 23 rain days are lost due to severe storms. This leaves only 18 days for possible modification, or 43 percent of the summer total. Thus, the yield benefits would amount to only 43 percent of those compiled from the field experiment Treatment 3, applied over the five years 1987-1991, produced a yield increase of 113 kg/ha in corn and a decrease of 6 kg/ha in soybeans. This corn yield increase, when reduced to 43 percent, translates regionally to an average annual income increase of $2.98 million. The soybean loss due to the reduced soybean yields amounts to $0.30 million. Factoring in the operational costs, this increase results in a benefit-cost ratio of 2.7.

Treatment 6: 25 Percent Increases on Moderate Rain Days

Moderate rainfalls (2.5 to 25.4 mm) occur over at least half the simulated project area, on the average, on 16 days each summer. Climatic factors reduce this to nine days available for seeding, and severe storm conditions reduce this by six days, to only 20 percent of the rain days at a point.

The average five-year effects of this treatment reduced corn yields by 227 kg/ha and soybean yields by 238 kg/ha. Since the yield effect achieved regionally is only 20 percent of the potential, the resulting changes would be 45.4 kg/ha less in corn and 47.6 kg/ha in soybeans. In the simulated project area, planted with 7,280 km^2 of corn and 5,200 km^2 of soybeans, the average annual five-year income effect represents a loss of $2.6 million in corn yields, and $5.5 million in soybean yields. The net regional effect is a loss of $8.1 million.

40 Percent Rain Increase in 1988

The major one-year benefit from increased rainfall would come from a 40 percent increase to all rain days when applied in an extremely hot and dry summer like 1988. Calculations were based on the yield increases on the experimental plots that received the 40 percent treatment. They were applied to the simulated project area, using actual rainfall and excluding nocturnal and severe weather events. The result was an income increase of $41.1 million in corn and $2.7 million in soybeans, for a regional gain of $43.7 million. Thus, if a rain enhancement technology capable of 40 percent increases in all rain conditions could be applied during hot and dry summers, which represent 14 percent of all summers in Illinois, major economic benefits would be realized.

Using Summer Rain Predictions in Seeding Project Decisions

These benefits also require a capability to accurately predict a dry summer by early June. As shown for the other treatments evaluated, cloud seeding to increase rainfall appears to be of lesser economic consequence in moderate to wet summers in the deep soils and humid climate of the Corn Belt. Several of the added rain treatments, when applied continuously over the five-year test period, even led to net financial losses. This situation indicates that if rainfall enhancement is to be of substantial benefit in Illinois and the Midwest, knowledge of the coming summer precipitation conditions is needed on June 1. This is the beginning of the seasonal period of crop moisture stress, and the point when a decision to conduct a cloud seeding project should be made.

The use of seasonal precipitation predictions was investigated as a means to make informed decisions about the use of cloud seeding to enhance summer rainfall. Existing climate-based seasonal precipitation predictions for areas of Illinois indicate whether summer rainfall will be above average (upper third of the values), near average (middle third), or below average (lower third of the possible values). An operational test of the prediction skill (Changnon and Hsu, 1985) revealed that summer-season rainfall predictions were correct 58 percent of the time. Twenty-five percent of the predictions were off by one level (e.g., a prediction of above average and average occurred), and 17 percent were off by two levels (a prediction of above average and below average occurred, or vice versa).

The findings on the effects of added water on the test plots (i.e., cloud seeding effects) and the existing predictive skill for the summer season were combined into an assessment of impacts on yields and income. This impact study was made for the five summers of 1987-1991 when the detailed results of augmented rainfall effects were available. Recall that the sampled years do not represent all types of summer weather conditions, although the wide range of conditions served as a useful test of the range of economic outcomes, given the use of the predictions.

Potential Economic Gains

The possible yields were evaluated in terms of an economic gain over a region where a cloud seeding program might occur. This analysis used revenue per hectare as a unit. The variables were the values of yields under three of the ten rain treatments, the predictive skill, the unit price of corn and soybeans, and an area model of a typical modification project over 13,000 km^2. A unit cost for the modification was also included. The economic gain (revenue minus cost) was used to assess the value of the existing predictive skill and to compare it to actual situations, where forecasts are not used and rain augmentation is not attempted.

Table 18 shows the average yield obtained for corn and soybeans in each year of the study, using treatments 1, 3, and 4: no augmentation, 25 percent augmentation, and 40 percent augmentation, respectively. Lack of corn values in 1987 and soybean values in 1991 made it necessary to estimate yields based on data from surrounding fields. For example, if the 40 percent augmentation had been applied in 1991, a dry year, the corn yield would have been 7,743 kg/ha.

A set of five-year forecast scenarios was generated with the predictive skill found in Changnon and Hsu (1985). Compared to the actual weather conditions in the study period, the three summer-season rainfall levels were predicted correctly in twenty possible scenarios (60 percent); one season was off by one level (20 percent); and one season was off by two levels (20 percent). Ten forecast combinations of the 20 that satisfied this skill level are presented in table 19.

For each five-year forecast, the following strategy was applied:

1. If the forecast was for a dry summer, apply treatment 4, 40 percent augmentation on all potential rain days.
2. If average summer rainfall was forecast, apply treatment 3,25 percent augmentation on all rain days.
3. For a wet summer, apply treatment 1, no augmentation.

This strategy was based on the findings of the five-year crop experiment. Although results of one wet summer (1987) indicated that 25 percent more rain was slightly better than no added rain, outcomes were assessed with no rain increase in wet summers, since past research had shown that rainfall increases in most wet summers reduced yields (Huff and Changnon, 1972).

The revenue per hectare in year i, using the simulated area land-use information, and assuming $0.08 and $0.22 as the cost

Table 18. Corn and Soybean Yields for Three Rain Treatments in the Five-Year Experiment (avg kg/ha)

	Tre atment					
Year	*Natural rainfall (1)*		*25% added to all rains (3)*		*40% added to all rains (4)*	
	Corn	*Soybeans*	*Com*	*Soybeans*	*Corn*	*Soybeans*
1987	8,290e	1,892	8,038e	1,800	6,782e	1390
1988	6,262	1,998	6,927	2,179	8,424	2,069
1989	14,412	3,715	15,382	3,676	13,936	3,555
1990	12335	2333	11,229	2,459	12,098	2320
1991	7381	2,092e	7,221	2,228e	7,743	2363e

Notes: e = estimated values using local yields.

Table 19. Ten Forecast Scenarios and Actual Precipitation Conditions, 1987-1991

Forecast scenario	*1987*	*1988*	*1989*	*1990*	*1991*
Actual weather	wet*	dry*	avg*	wet	dry
87d,89d	dry	dry	dry	wet	dry
87d,90a	dry	dry	avg	avg	dry
87d, 91a	dry	dry	avg	wet	avg
87d, 89w	dry	dry	wet	wet	dry
87d,88a	dry	avg	avg	wet	dry
87a, 90d	avg	dry	avg	dry	dry
87a, 91w	avg	dry	avg	wet	wet
87a, 88w	avg	wet	avg	wet	dry
88d,89d	wet	dry	dry	dry	dry
89d, 91w	wet	dry	dry	wet	wet

Notes: Scenario "87d, 89w" was incorrectly predicted "dry" (off by two levels) in 1987 and "wet" (off by one level) in 1989, as compared to the actual weather.

*Wet represents the upper third of the range of summer values; dry is the lower third; and avg (average) is the middle third.

Forecast scenarios are applied with the skill level found in Changnon and Hsu (1985).

of a kilogram of corn and soybeans, respectively, is given as:

R(i,t) = Corn yield (i,t) x $0.08 x 48% +
soy yield (i,t) x $0.22 x 39% - C (i,f)

where C (i,f) is the cost of augmentation per hectare of land planted, based on the forecast f in year i (f could range from dry, to average, or wet); while t in R(i,t) and the yield signify the augmentation treatment applied; 1, 3, or 4. Based on a Si-million cost for the area augmentation effort, with 87 percent of 13,000 km^2 planted in the target area, the cost for augmentation is $0.88 per hectare. For f = dry or average, C (i,f) = $0.88/ha; and f = wet, men C (i, f) = $0.

R(i,t) can be interpreted as an area-averaged estimate of return in dollars per hectare, or alternatively, the dollar value to a farmer who planted approximately 48 percent of the farm in corn and 39 percent in soybeans, if augmentation, t, is applied. The forecast indication, f, was suppressed in R(i,t) for clarity. In actuality, the treatment, t, depends on the forecast, as outlined in the strategy above. The focus was on the economic gain obtained by augmentation:

$$E(i,t) = R(i,t) - R(i, \text{natural})$$

Specifically, me five-year average of E(i,t), when i=1987 to 1991, was the objective function investigated. The gain obtained using a sample forecast scenario is shown in table 20.

Five-Year Average Gains

The five-year average gain was calculated for each of the 20 forecast scenarios (figure 31). The average gain based on all scenarios was $9.50 per hectare, ranging from a $3.60 loss to a $22.50 gain. Based on the experiment's results with annual average revenue of $586.80/ha with no augmentation, a gain of 1.6 percent could be expected, ranging from a 0.6 percent loss to a 3.8 percent gain.

Gains and losses due to rain augmentation fluctuated in individual years, but the five-year average smooths these fluctuations. For example, using the same forecast scenario, me extremes ranged from a $101.90 loss per hectare in 1987 to a gain of $88.20 in 1988, but the five-year average is a small loss of $1.90. The yearly analysis reveals annual losses 16 percent of the time, no gain or loss 38 percent of the time, and a gain 46 percent of the time. Clearly the utility of a weather modification project lies in its repeated use over several years, if predictive skill is to be used to its best advantage.

In figure 31, the gains from use of the predictions are found in the upper portions of the bars generated by all possible forecast scenarios (3^5 = 243 of them). Table 21 shows the relative chances of gains and losses, reflecting the fact that use of the predictions would produce a gain in income 85 percent of the time.

Had there been perfect knowledge of the precipitation levels of the five summers, 1987-1991, and the best rain treatments were applied based on this knowledge, then the maximum possible gain would have been attained, $26.20 per hectare, as shown in table 22. Unfortunately, the forecast skill level is not perfect, so in some years the improper treatment would be applied due to an erroneous forecast, and gains would be suboptimal. The expected gain in this case would be $9.50 per hectare, roughly one-third of which would be achieved with a perfect forecast.

Nevertheless, this analysis shows that even if the existing predictive skill had been used, the five-year (1987-1991) average would have been a gain 85 percent of the time. The best

Table 20. Economic Gain for Forecast Scenario 87d, 90a, ($/ha)

Year	*Forecast**	*Treatment strategy (%)*	*Revenue w/aug. ($/ha.)*	*Revenue w/o aug. ($/ha.)*	*Gain/Loss*
1987	dry	40%	378.80	480.70	-101.90
1988	dry	40%	500.10	411.90	88.20
1989	avg	25%	905.20	872.20	33.00
1990	avg	35%	641.30	698.70	-57.40
1991	dry	40%	499.20	970.60	28.60
5-year avg			585.80	586.80	-1.90

Notes: *avg. = Near-average summer rainfall.
Forecast scenarios are described in table 52.

gain, from a 60 percent skill level, would be $22.50, which approaches the maximum possible gain.

Rain Augmentation with and without Forecasting

A comparison of the gains using rain augmentation with and without forecasting was also instructive. If 40 percent augmentation were applied every year over the five-year study period, without forecasts, it would have resulted in a net regional gain of $3.41 million (table 22), equal to about three times the $1-million project cost Use of the existing predictive skill produced an average gain of $12.4 million, about four times the gain from augmentation without the use of predictions. This is equivalent to an expected gain of $2.60 per hectare, which is 0.4 percent of the crop income per hectare as calculated on a regional basis.

If existing summer rainfall predictions were coupled with cloud seeding (and if seeding could deliver rain increases of 25 to 40 percent), the expected gain of $9.50 per hectare ($12.4 million regionally) represents 1.6 percent of the income without seeding. If such rain enhancement and prediction capabilities existed, the expected additional gain would be 4.5 percent of the total income.

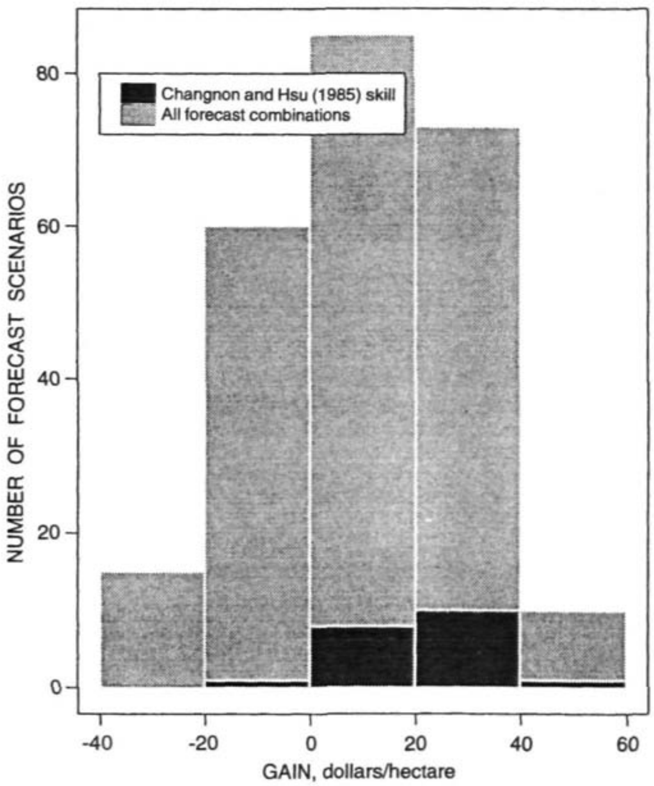

Figure 31. Average five-year economic gain to be realized through 20 forecast scenarios

Summary

The integration of agricultural, climatic, logistic, economic, and legal factors affecting rainfall enhancement to increase crop yields in Illinois revealed that expected increases would be less than those calculated from the 5-year open-area experiment. The yield increases that could be expected from a 25 percent rain increase on days with moderate rains would amount to only 20 percent of the total yield increase based on the open-area plot data for 1987-1991. With the various limitations, the yield increase with a 25 percent rainfall addition on all rain days would be only 43 percent of the experimental increases.

The crop yield increases that could be realistically expected for a typical area experiencing rainfall modification are greatly reduced due to the inability to take advantage of seedable events occurring at night and during severe weather conditions. Moreover, since rainfall additions on days with light rain (<2.5 mm) exhibited few positive yield effects, optimal increases would likely not be achieved on days with generally light or moderate rainfall over sizable portions of the project area.

If rainfall increases could be accomplished, the costs to modify most seedable clouds during moderate to heavy rain events were estimated at $1 million per summer for a project area of 13,000 km^2. This cost was compared to the estimated average yield benefits due to the best rain treatments in the simulation area:

- Treatment 3 (25 percent increases on all days) resulted in an annual average $2.9 million income increase.
- Treatment 4 (40 percent rain increase on all rain days) resulted in an average annual regional income increase of $3.4 million annually. These outcomes are based on weather years like those sampled during 1987-1991.

The best rainfall increase in a hot/dry summer, if scientifically possible, would be from additions of 40 percent to all rains or to heavy rains >25.4 mm. However, 40 percent rainfall increases were found to be a poor choice for summers with above-average rainfall. Thus, the selection of the best treatment for a given type of summer requires a reasonably accurate prediction of the three-month rainfall and temperature conditions at the outset of summer.

If perfect knowledge of the precipitation levels for each of the five summers (1987-1991) had been available in advance, and if rain treatments could have been applied based on this knowledge, then the maximum possible gain, $26.20 per hectare, would have been attained. Unfortunately, since the existing forecast skills are not perfect, improper treatment would be applied in some years, and the gain would be less than optimal. Yet if seasonal rainfall predictions had been used with existing skill over the five-year experimental period, financial gains would have been achieved 85 percent of the time. The use of these predictive skills would have generated an average regional income increase of $12.4 million, about four times the gain from precipitation augmentation without use of predictions. This gain represents 1.6 percent of the regional income without seeding.

Collectively, these findings do not suggest a potential for major economic benefits from rainfall enhancement to Illinois crops at today's prices, even with potential capability to increase summer rain 25 to 40 percent above natural levels.

Recommendations

The open-area plot results provide useful guidance in two areas of weather modification. One relates to future use of cloud seeding to enhance summer rainfall in the deep-soil areas of Illinois and the Corn Belt. The other concerns future research on purposeful rain enhancement in Illinois and the Midwest.

The 1987-1991 results, albeit based on a five-year sample, are not encouraging about the use of cloud seeding to achieve

Table 21. Relative Chances of Gain/Hectare with 60 Percent Forecast Skill

Gain(loss) ($/ha)	*% of time*
5 - 0	15
0 - 5	20
(6) - (10)	15
(11) - (15)	20
(16) - (20)	20
(21) - (30)	10

Table 22. Values of Illinois Crop Production and Income Gains due to Rain Enhancement with and without Forecasts, 1987-1991

	Seeded area	*Single hectare in seeded area*
Total income without seeding	$762.8 million	$586.80
Expected additional income with treatment 4* on all rain days	$3.41 million	$2.60
Expected additional income with treatment 4 and existing forecast skill	$12.4 million	$9.50
Expected additional income with treatment 4 and perfect knowledge of summer rainfall	$34.1 million	$26.20

Notes: *This treatment was found to be the best of the ten tested in every year of the 1987-1991 period.
Treatment 4 = 40 percent added on all rain days in all five years.
Seeded area = 13,000 km^2.

major yield increases in the deep-soil areas of Illinois and the Corn Belt. Even with a perfectly defined technology capable of "delivering" 25 percent rainfall increases, only small yield enhancements could be achieved in many years. Note that a capability to produce such increases has not been established (Changnon et al., 1991). The development of such a capability awaits years of expensive research — if indeed it can be achieved. The results of this research indicate that with current constraints relating to night seeding and severe weather conditions, only marginal benefits could be produced, except in occasional dry summers.

Meteorologically, the capability to predict the type of summer precipitation, at least by early June, would be invaluable in deciding which rain treatment to employ (given that one existed). Knowledge of future hot dry conditions would call for seeding of all possible rain events. Knowledge of near-normal rain conditions would call for seeding only moderate to heavy rains during critical crop periods from late June to early August, depending on the crop stages. Knowledge of an upcoming wet summer would eliminate any rain enhancement *Existing climatological- or statistical-based techniques to predict regional summer-season rainfall (above normal, near normal, or below normal) should be used on a continuing, year-to-year basis to decide on the need for cloud seeding.*

A second major meteorologically based recommendation relates to modification capabilities. This study has shown that meaningful rainfall increases in near-normal and dry years necessitate cloud seeding at night. *Seeding techniques should be developed that allow for the delivery of seeding material into nighttime convective clouds.*

The results of this research have shown that to achieve agricultural benefits, the seeding technology must be able to produce 25 to 40 percent increases under most rain conditions. *A major research objective is to develop a cloud seeding technology capable of increasing summer rainfall conditions by 25 percent or more.*

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APPENDIX TABLES

Table A1. Assignment of Rain Days and Rain Amounts to Historical Wet Periods in an Average Summer

	Rainfall amount as a percentage of the monthly totals (%)			*Rain-day frequency*	
Period	*Historical*	*Expected*	*Assigned*	*Expected*	*Selected*
7-15 June	47	30	54	3	4
23-27 June	22	16	20	2	3
2-7 July	39	20	58	1	2
1-3 August	20	10	22	1	2
10-18 August	54	30	57	3	4

Table A2. Total Water during each Month in the Open-Area Experiment, 1987-1991

		Precipitation treatments (mm)										
Year	*Date of planting*	*1*	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*	*10*	*Average*
						Planting to June 1						
1987	28 May	13.3	13.3	13.3	13.3	13.3	133	13.3	13.3	13.3	133	13.3
1988	12 May	25.9	25.9	25.9	25.9	25.9	25.9	25.9	25.9	25.9	25.9	25.9
1989	13 May	115.1	115.11	115.1	115.1	115.1	115.1	115.1	115.1	115.1	115.1	115.1
1990	30 May	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
1991	15 May	121.9	121.9	121.9	121.9							121.9
						June						
1987	28 May	126.8	1395	1585	1775	130.2	135.4	1405	135.9	1633	1273	1435
1988	12 May	75.9	83.5	94.9	1063	78.4	82.2	85.9	75.9	75.9	75.9	83.5
1989	13 May	127.6	140.4	1595	178.6	131.1	1363	141.4	1363	162.6	129.8	144.4
1990	30 May	211.6	232.8	2645	296.2	219.9	232.4	244.9	223.8	2605	214.0	240.1
1991	15 May	16.8	18.5	21.0	23.5							20.0
						July						
1987	28 May	199.1	219.0	248.9	278.7	207.1	219.0	230.9	210.4	244.1	201.9	225.9
1988	12 May	92.5	101.8	115.6	1295	96.2	101.9	1075	97.9	114.0	93.0	105.0
1989	13 May	45.3	49.8	56.6	63.4	49.8	56.6	633	45.3	45.3	45.4	52.1
1990	30 May	92.2	101.4	1153	129.1	98.3	1073	116.4	95.2	1043	92.8	105.2
1991	15 May	65.8	72.4	82.3	92.1							78.2
						August						
1987	28 May	127.2	139.9	159.0	178.1	132.7	140.9	149.0	133.9	153.8	129.6	144.4
1988	12 May	31.6	34.8	39.5	44.2	345	38.7	43.0	31.6	31.6	32.8	36.2
1989	13 May	1085	119.4	135.6	151.9	119.0	134.9	150.7	1085	1085	109.7	124.7
1990	30 May	63.0	69.3	78.8	88.2	69.1	78.3	87.5	63.0	63.0	63.7	72.4
1991	15 May	57.7	63.5	72.1	80.8							68.5

Precipitation treatments:
1. Natural rainfall.
2. Increase all daily rains 10 percent.
3 . Increase all daily rains 25 percent
4. Increase all daily rains 40 percent.
5. Increase all daily rains of 254 mm to 25.4 mm by 10 percent (moderate rain).
6. Increase all daily rains of 254 mm to 25.4 mm by 25 percent (moderate rain).
7. Increase all daily rains of 254 mm to 25.4 mm by 40 percent (moderate rain).
8. Increase all daily rains above 25.4 mm by 10 percent (heavy rain).
9. Increase all daily rains above 25.4 mm by 40 percent (heavy rain).
10. Increase all daily rains less than 254 mm by 40 percent (light rain).

Table A3. Natural Daily Rainfall for May, June, July, and August, 1987-1991 (mm)

	May					June					*July*					*August*				
Dey	1987	1988	1989	1999	1991	1987	1988	1989	1990	1991	1987	1988	1989	1999	1991	1987	1988	1989	1990	1991
1					7.1			1.8			3.4				13					
2			0.3			30.5			6.1						0.3					
3				15.5	19.8			21.1					4.3			1.0			4.3	
4			4.1	9.9							9.1									
5			1.3	5.6	50.8			0.8			6.1						3.8	0.8		7.1
6			0.3						216		4.6									417
7									211											13
8		13.3	17.3				8.1		1.8		10					114				13
9			8.1	17.5					13		110			5.1	9.1		9.7			
10				0.3	0.3							0.5			117					
11	11.9						25.4*	0.5		0.3				30.2	33.8				19.3	
12		0.3		440				2.8			13	0.8		1.5	6.6		01			
13			0.3			0.5			0.3		13			4.3		1.0		1.0		
14	0.3				36.8				1.0			19				1.8		0.8		
15				18.8	0.8					117	4.3			109						
16		1.8		71.1	41.1					0.5						7.9				
17				4.3	117				30.5							10				1.8
18	41.4				1.0			2.5				23.4	0.3				16			
19			43.9	4.6		4.6			4.6				17.8				1.0			0.8
20	11					32.5			60.7			5.1	112	10					18.8	
21			1.8	0.5	311	0.8	17.0*			3.3			10.7	102		196			0.5	
22		17.3	9.9				25.4*		110					113			4.1	219	13	
23		5.6		2.8				52.3									4.3	23.1		
24		0.8		0.8																
25	10.4		58.9	20.8	10	212						53.8				11.7				
26				1.0	5.3			311			10.9					515		0.5		
27								10.7			13.0					33.0	13	14.2		
28	0.3	0.3							11.9									18.3		0.5
29					1.3	112			31.0		0.3			107				216	18.8	
30	12.7				4.3	17.3			0.5		112.3									
31	0.3				0.3						6.1					13		13		
Total	80.4	39.6	147.3	219.3	236.7	126.8	719	127.6	211.6	168	199.1	92.5	45.3	912	65.8	127.2	31.6	108.5	610	57.7

Notes: *Irrigation without any natural rainfall
Rainfall was measured at the experimental plots.

Table A4. Natural Rainfall on Sheltered Plots, October 31 through Date of Planting, and Date of Planting to First Water Treatment

Year	*Date of planting*	*October to date of planting (nun)*	*Date of planting to first water treatment (mm)*
1987	28 May	448.6	13.0
1988	12 May	462.8	25.8
1989	13 May	517.1	55.6
1989	31 May	632.2	79.3
1990	24 May	573.0	109.7
1990	30 May	594.9	56.4
1990	5 June	601.0	81.8
1991	15 May	581.7	121.9
1991	29 May	7025	5.9

Note: Rainfall was measured at the official NWS Champaign weather station.

Table A5. Estimated Dates of Corn Growth Stages

Year	*Stage 1: Planting*	*Stage 2: Tassel initiation*	*Stage 3: Ear initiation*	*Stage 4: End of row set*	*Stage 5: Silking*	*Stage 6: End of lag phase*	*Maturity*
1987	28 May	20 Jun	26 Jun	8 Jul	24 Jul	7 Aug	24 Sep
1988	12 May	12 Jun	19 Jun	30 Jun	15 Jul	30 Jul	9 Sep
1989	13 May	15 Jun	21 Jun	3 Jul	18 Jul	2 Aug	16 Sep
	31 May	26 Jun	2 Jul	12 Jul	28 Jul	13 Aug	9 Oct
1990	24 May	23 Jun	29 Jun	10 Jul	28 Jul	16 Aug	8 Oct
	30 May	27 Jun	3 Jul	16 Jul	2 Aug	20 Aug	23 Oct
	5 Jun	1 Jul	7 Jul	19 Jul	6 Aug	24 Aug	26 Oct*
1991	15 May	8 Jun	14 Jun	24 Jun	8 Jul	22 Jul	1 Sep
	29 May	20 Jun	26 Jun	5 Jul	20 Jul	3 Aug	13 Sep

Notes: *Frost occurred on 26 October before the crop had accumulated the number of growing degree days necessary for maturity.
Dates were computed using growing degree days.

Table A6. Estimated Dates of Soybean Growth Events

Year	*Stage 1: Planting*	*Stage 2: First unifoliate*	*Stage 3: Floral induction*	*Stage 4: First flower*	*Stage 5: Physiological maturity*
1987	28 May	11 Jun	21 Jun	10 Jul	31 Aug
1988	12 May	30 May	10 Jun	29 Jun	21 Aug
1989	13 May	31 May	11 Jun	30 Jun	23 Aug
1990	24 May	10 Jun	20 Jun	8 Jul	31 Aug
	30 May*	15 Jun	25 Jun	13 Jul	3 Sep
1991	15 May	27 May	6 Jun	24 Jun	18 Aug

Notes: *Open area planted on this day in 1990.
Dates were computed using the soybean phenology model in SOYGRO (Jones et al., 1991).

Table A7. Water Received by Mobile Shelter Corn Plots

Year	Date of planting	Precipitation treatments (mm) Dry	Dry +25%	Avg	Avg +25%	Wet	Wet +25%	Mean
		Stage 1: Planting to tassel initiation						
1987	28 May	88.1	993	115.6	133.8	119.2	138.2	115.7
1988	12 May	37.1	25.9	44.5	49.2	45.8	50.8	44.6
1989	13 May	164.9	177.4	1875	205.8	193.1	212.7	190.2
1989	31 May	69.3	86.7	99.8	125.0	130.8	163.6	1125
1990	24 May	95.7	100.0	103.6	109.9	104.6	111.1	104.2
1990	30 May	107.6	1203	1305	149.0	158.9	1843	141.8
1990	5 Jun	78.7	84.1	86.6	94.0	119.1	1345	99.5
1991	15 May	1413	1463	148.9	155.9	152.2	160.0	150.7
1991	29 May	55.6	68.1	78.2	965	83.5	103.4	81.0
		Stage 2: Tassel initiation to ear initiation						
1987	28 May	15.2	19.0	18.0	22.5	43.4	543	28.7
1988	12 May	33.2	41.5	53.3	66.6	55.6	69.5	53.3
1989	13 May	4.3	5.4	9.4	11.8	9.4	11.8	8.7
1989	31 May	1.8	23	1.8	2.3	9.4	11.8	4.9
1990	24 May	4.3	5.4	43	5.4	29.7	37.1	14.4
1990	30 May	0.0	0.0	0.0	0.0	6.9	8.6	2.6
1990	5 Jun	20.8	26.0	41.2	51.5	485	60.6	41.4
1991	15 May	29.2	36.5	44.2	55.3	465	58.1	45.0
1991	29 May	15.2	19.0	18.0	22.5	43.4	54.3	28.7
		Stage 3: Ear initiation to end of row set						
1987	28 May	22.6	283	43.0	53.8	57.4	71.8	46.2
1988	12 May	17.0	21.3	19.8	24.8	52.3	65.4	33.4
1989	13 May	17.0	21.3	19.8	24.8	52.8	66.0	33.6
1989	31 May	22.8	28.5	50.1	62.6	63.3	79.1	51.1
1990	24 May	22.8	28.5	50.1	62.6	69.9	87.4	53.6
1990	30 May	22.8	28.5	52.4	655	69.4	86.8	54.2
1990	5 Jun	2.0	2.5	11.2	14.0	21.4	26.8	13.0
1991	15 May	17.5	21.9	25.4	31.8	26.4	33.0	26.1
1991	29 May	22.6	28.3	43.0	53.8	57.4	71.8	46.2
		Stage 4: End of row set to silk						
1987	28 May	12.9	16.1	34.4	43.0	63.1	78.9	41.4
1988	12 May	22.8	28.5	52.4	65.5	69.9	87.4	54.4
1989	13 May	22.8	28.5	52.4	65.5	69.9	87.4	54.4
1989	31 May	13.7	17.1	30.3	37.9	53.1	66.4	36.4
1990	24 May	13.7	17.1	30.3	37.9	53.1	66.4	36.4
1990	30 May	21.4	26.8	35.7	44.6	63.6	79.5	45.3
1990	5 Jun	30.5	38.1	57.3	71.6	87.7	109.6	65.8
1991	15 May	25.1	31.4	45.5	56.9	84.3	105.4	58.1
1991	29 May	2.0	2.5	11.2	14.0	21.4	26.8	13.0

Table A7. Concluded

Year	Date of planting	Precipitation treatments (mm) Dry	Dry +25%	Avg	Avg +25%	Wet	Wet +25%	Mean
		Stage 5: Silk to end of lag phase						
1987	28 May	20.1	25.1	34.4	43.0	57.2	715	41.8
1988	12 May	20.4	25.5	34.4	43.0	57.2	715	42.0
1989	13 May	21.7	27.1	35.7	44.6	63.6	795	45.4
1989	31 May	21.6	27.0	35.1	43.9	50.6	63.3	40.2
1990	24 May	40.7	50.9	78.0	97.5	93.8	1173	79.7
1990	30 May	38.1	47.6	82.7	103.4	89.9	112.4	79.0
1990	5 Jun	31.0	38.8	63.1	78,9	67.8	84.8	60.7
1991	15 May	12.9	16.1	34.4	43.0	63.1	78.9	41.4
1991	29 May	30.5	38.1	57.3	71.6	87.7	109.6	65.9
		Stage 6: End of lag phase to August 31						
1987	28 May	35.3	44.1	68.4	85.5	125.4	156.8	85.9
1988	12 May	45.7	57.1	91.3	114.1	155.9	194.9	109.8
1989	13 May	44.4	55.5	90.0	1125	1495	186.9	1065
1989	31 May	30.5	38.1	62.6	78.3	1155	144.4	78.2
1990	24 May	11.4	14.3	19.7	24.6	72.3	90.4	38.8
1990	30 May	6.3	7.9	7.3	9.1	59.6	74.5	27.4
1990	5 Jun	4.3	5.4	5.3	6.6	57.6	72.0	25.2
1991	15 May	54.9	68.6	1025	128.1	171.4	2143	1233
1991	29 May	35.3	44.1	68.4	85.5	125.4	156.8	85.9

Notes: Corn in the mobile shelter experiment was planted on 28 May 1987,12 May 1988, 13 May 1989, 30 May 1990, and 15 May 1991.
The first dates of planting in the planting date study were 13 May 1989, 24 May 1990, and 15 May 1991.
The second dates of planting were 31 May 1989, 5 June 1990, and 29 May 1991.

Table A8. Total Water Received by the Open-Area Corn Plots During Each Crop Growth Stage

Year	Date of planting	*Precipitation treatments (mm)* 1	2	3	4	5	6	7	8	9	10	Mean
						Stage 1: Planting to tassel initiation						
1988	12 May	59.4	60.2	61.5	62.7	60.2	61.5	62.7	59.4	59.4	59.4	60.6
1989	13 May	142.0	144.7	148.7	152.8	144.4	148.0	151.5	142.0	142.0	143.2	145.9
1990	30 May	190.8	207.6	232.8	258.0	197.9	208.6	219.3	199.9	227.2	192.0	213.4
1991	16 may	19.3	20.7	22.7	24.7							21.9
						Stage 2: Tassel initiation to ear initiation						
1988	12 May	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
1989	13 May	2 5	2.8	3.2	3.6	2 5	2 5	2 5	2 5	23	23	23
1990	30 May	42.9	47.2	53.7	60.1	44.1	45.9	47.7	46.0	55.3	42.9	48.6
1991	16 May	3.3	3.6	4.1	4.6							3.9
						Stage 3: Ear initiation to end of row set						
1988	12 May	42.4	42.4	42.4	42.4	42.4	42.4	42.4	42.4	42.4	42.4	42.4
1989	13 May	102.4	112.6	128.0	143.3	103.9	106.1	108.4	111.1	137.3	102.4	115.6
1990	30 May	1.0	1.1	1.3	1.4	1.0	1.0	1.0	1.0	1.0	1.4	1.1
1991	16 May	2.5	2.8	3.2	3.6							3.0
						Stage 4: End of row set to silking						
1988	12 May	10.2	11.2	12.7	14.2	11.0	12.4	13.7	10.2	10.2	10.7	11.7
1989	13 May	0.3	0.3	0.3	0.4	0.3	0.3	0.3	0 3	0 3	0.4	0.3
1990	30 May	87.1	95.8	108.9	122.0	92.7	101.0	109.3	90.1	99.2	87.7	99.4
1991	16 May	63.2	69.6	79.1	88.5							75.1
						Stage 5: Silking to end of lag phase						
1988	12 May	82.3	90.5	102.9	115.2	85.1	89.4	93.7	87.7	103.8	82 3	93.3
1989	13 May	40.6	44.7	50.8	56.9	44.7	50.8	56.9	40.6	40.6	40.6	46.7
1990	30 May	23.6	26.0	29.5	33.1	26.0	29.5	33.1	23.6	23.6	23.6	27.2
1991	16 May	0.0	0.0	0.0	0.0							0.0
						Stage 6: End of lag phase to maturity						
1988	12 May	50.3	53.5	58.4	63.3	53.1	57.4	61.7	50.3	50.3	51.9	55.0
1989	13 May	224.0	234.9	251.1	267.4	234.6	250.4	266.2	224.0	224.0	225.2	242.2
1990	30 May	145.3	149.2	155.1	161.0	149.0	154.7	160.3	145.3	145.3	146.0	151.1
1991	16 May	99.6	105.3	114.0	122.6							110.4

Precipitation treatments:

1. Natural rainfall.
2. Increase all daily rains 10 percent.
3. Increase all daily rains 25 percent.
4. Increase all daily rains 40 percent
5. Increase all daily rains of 2.54 mm to 25.4 mm by 10 percent (moderate rain).
6. Increase all daily rains of 2.54 mm to 25.4 mm by 25 percent (moderate rain).
7. Increase all daily rains of 2.54 mm to 25.4 mm by 40 percent (moderate rain).
8. Increase all daily rains above 25.4 mm by 10 percent (heavy rain).
9. Increase all daily rains above 25.4 mm by 40 percent (heavy rain).
10. Increase all daily rains less than 254 mm by 40 percent (light rain).

Table A9. Average Maximum and Minimum Temperatures for the Corn Growth Stages (°C)

Year	*Date of planting*	*Stage 1: Planting to tassel initiation*		*Stage 2: Tassel initiation to ear initiation*		*Stage 3: Ear initiation to end of row set*		*Stage 4: End of row set to silk*		*Stage 5: Silk to end of lag phase*		*Stage 6: End of lag phase to maturity*	
		Max	*Min*	*Max*	*Min*	*Max*	*Min*	*Max*	*Min*	*Max*	*Min*	*Max*	*Min*
1987	28 May	30.7	17.2	29.1	18.3	28.1	17.1	29.9	18.2	31.5	20.0	27.2	14.8
1988	12 May	28.6	11.4	33.0	14.8	32.4	17.4	33.9	18.5	31.4	18.5	30.7	16.4
1989	13 May	24.8	13.4	28.1	15.6	29.7	175	30.9	18.1	28.6	19.3	27.4	16.9
	31 May	28.1	16.1	28.0	15.6	31.6	19.9	28.4	18.0	29.0	16.3	24.8	13.7
1990	24 May	25.9	14.4	28.5	16.6	29.8	18.2	26.0	16.6	26.0	15.1	26.1	14.7
	30 May	26.6	15.0	29.1	17.4	27.2	17.2	27.7	16.7	26.6	16.1	23.4	12.0
	5 Jun	27.4	16.2	29.3	17.0	26.8	17.1	26.9	16.6	26.4	16.5	22.8	11.1
1991	15 May	28.7	18.0	32.0	18.8	29.8	18.7	32.9	20.5	30.5	19.7	29.7	18.1
	29 May	30.3	18.4	29.5	19.0	32.7	20.0	30.6	19.9	30.4	18.3	30.2	18.1

Table A10. Water Received by the Mobile Shelter Soybean Crop

		Precipitation treatments (mm)						
Year	*Date of planting*	*Dry*	*Dry +25%*	*Avg*	*Avg +25%*	*Wet*	*Wet +25%*	*Mean*
		Stage 1: Planting to unifoliate						
1987	28 May	54.9	57.7	6Z3	66.9	63.8	68.8	624
1988	12 May	25.9	25.9	25.9	25.9	25.9	25.9	25.9
1989	13 May	115.1	115.1	115.1	115.1	115.1	115.1	115.1
1990	24 May	78.7	78.7	78.7	78.7	78.7	78.7	78.7
1991	16 May	116.11	116.1	116.1	116.1	116.1	116.1	116.1
		Stage 2: Unifoliate to floral induction						
1987	28 May	71.8	89.8	114.3	142.9	167.9	209.9	132.8
1988	12 May	61.4	76.8	91.7	114.6	127.8	159.8	105.4
1989	13 May	71.1	88.9	101.6	127.0	133.3	166.6	114.8
1990	24 May	71.3	89.1	114.6	143.2	168.2	210.2	132.8
1991	16 May	59.9	73.5	87.6	108.1	93.2	115.1	89.6
		Stage 3: Floral induction to flower appearance						
1987	28 May	36.8	46.0	80.4	100.5	123.3	154.1	90.2
1988	12 May	38.3	47.9	79.9	99.9	147.4	184.3	99.6
1989	13 May	36.8	46.0	80.4	100.5	123.3	154.3	90.2
1990	24 May	32.8	41.0	68.5	85.6	97.4	121.8	74.5
1991	16 May	37.1	46.4	72.2	90.3	122.2	152.8	86.8
		Stage 4: Flower appearance to physiological maturity						
1987	28 May	65.8	82.3	128.0	160.0	219.2	274.0	154.9
1988	12 May	8Z6	103.3	170.8	219.6	274.5	214.3	177.5
1989	13 May	82.6	103.3	170.8	213.5	223.4	279.3	178.8
1990	24 May	67.8	84.8	129.7	162.1	234.5	293.1	162.0
1991	16 May	86.9	108.6	175.1	218.9	258.9	323.6	195.3

Table A11. Total Water Received by Soybeans, Open-Area Experiments

Year	Date of planting	*Precipitation treatments (mm)* 1	2	3	4	5	6	7	8	9	10
		Stage 1: Planting to unifoliate									
1987	28 May	43.8	43.8	43.8	43.8	43.8	43.8	43.8	43.8	43.8	43.8
1988	12 May	26.1	26.1	26.1	26.1	26.1	26.1	26.1	26.1	26.1	26.1
1989	13 May	115.0	115.0	115.0	115.0	115.0	115.0	115.0	115.0	115.0	115.0
1990	30 May	57.4	57.4	57.4	57.4	57.4	57.4	57.4	57.4	57.4	57.4
		Stage 2: Unifoliate to floral induction									
1987	28 May	38.4	42.2	48.0	53.8	38.9	39.6	40.2	41.7	51.4	38.9
1988	12 May	8.1	8.1	8.1	8.1	8.1	8.1	8.1	8.1	8.1	8.1
1989	13 May	24.2	26.6	303	33.9	26.3	29.5	32.6	24.2	24.2	25.4
1990	30 May	110.8	121.9	1385	155.1	1163	119.7	122.6	119.9	1473	110.8
		Stage 3: Floral induction to first flower									
1987	28 May	103.1	113.4	128.9	1443	110.4	1213	1045	105.9	114.4	103.9
1988	12 May	67.8	67.8	67.8	67.8	67.8	67.8	67.8	67.8	67.8	67.8
1989	13 May	103.4	113.7	1293	144.8	104.8	106.8	108.8	112.1	138.4	104.4
1990	30 May	84.5	93.0	105.6	1183	86.6	89.8	93.0	90.6	109.0	85.3
		Stage 4: First flower to physiological maturity									
1987	28 May	281.1	309.2	351.4	3935	290.2	303.8	3175	299.0	352.7	285.6
1988	12 May	124.1	1365	155.1	173.7	130.7	140.6	1505	1295	145.6	125.7
1989	13 May	153.8	169.2	1923	2153	168.8	191.4	214.0	153.8	153.8	155.2
1990	30 May	114.1	1255	142.6	159.7	125.0	141.4	157.8	114.1	114.1	116.0

Precipitation treatments:

1. Natural rainfall.
2. Increase all daily rains 10 percent
3. Increase all daily rains 25 percent
4. Increase all daily rains 40 percent
5. Increase all daily rains of 2.54 mm to 25.4 mm by 10 percent (moderate rain).
6. Increase all daily rains of 2.54 mm to 25.4 mm by 25 percent (moderate rain).
7. Increase all daily rains of 2.54 mm to 25.4 mm by 40 percent (moderate rain).
8. Increase all daily rains above 25.4 mm by 10 percent (heavy rain).
9. Increase all daily rains above 25.4 mm by 40 percent (heavy rain).
10. Increase all daily rains less than 254 mm by 40 percent (light rain).

Table A12. Average Maximum and Minimum Temperatures During the Soybean Growth Stages (°C)

Year	*Date of planting*	*Stage 1: Planting to first unifoliate*		*Stage 2: First unifoliate to floral induction*		*Stage 3: Floral induction to first flower*		*Stage 4: First flower to physiological maturity*	
		Max	*Min*	*Max*	*Min*	*Max*	*Min*	*Max*	*Min*
1987	28 May	29.1	15.6	33.0	19.9	28.5	17.6	30.6	19.3
1988	12 May	27.8	10.8	29.8	12.8	32.6	15.8	33.0	19.3
1989	13 May	23.7	12.4	26.7	14.2	28.8	16.6	29.2	17.8
1990	24 May	24.4	12.6	28.8	17.6	28.4	16.8	27.0	16.7
	30 May	263	14.3	26.8	16.2	28.3	17.8	27.3	16.7
1991	15 May	27.8	17.6	29.8	18.9	30.4	18.3	293	17.7

Table A13. Weather Variable Correlations at Different Growth Stages, Corn Mobile Shelter Experiment

		Stage 1			*Stage 2*			*Stage 3*			*Stage 4*			*Stage 5*			*Stage 6*		
Stage	*Variable*	*Max temp*	*Min temp*	*Precip*	*Max temp*	*Min temp*	*Precip*	*Max temp*	*Min temp*	*Precip*	*Max temp*	*Min temp*	*Precip*	*Max temp*	*Min temp*	*Precip*	*Max temp*	*Min temp*	*Precip*
1	Max temp	1.00	0.45	-0.55*	0.43	0.47*	0.57*	0.04	0.03	0.01	0.23	0.35	-0.09	0.76*	0.41	-0.22	0.35	0.05	0.10
	Min temp		1.00	0.40	-0.16	0.99*	-0.03	-0.60*	0.44	0.02	-0.26	0.40	-0.06	0.09	0.33	-0.02	-0.18	0.03	-0.01
	Precip			1.00	0.68*	0.33	-0.50*	-0.53*	0.24	0.22	-0.43	-0.00	0.26	-0.54*	0.07	0.31	-0.43	0.05	0.13
2	Max temp				1.00	-0.13	0.81*	0.73*	0.48*	-0.27	0.80*	0.59*	0.14	0.56*	0.11	-0.21	0.75*	0.44	0.28
	Min temp					1.00	-0.04	0.65*	0.39	0.08	-0.33	0.32	-0.08	0.02	0.19	0.05	-0.25	-0.10	-0.08
	Precip						1.00	0.67*	0.40	-0.05	0.78*	0.64*	0.46	0.76*	0.43	•0.09	0.80*	0.55*	0.66*
3	Max temp							1.00	0.26	•0.37	0.93*	0.47*	0.18	0.57*	0.32	-0.35	0.88*	0.68*	0.43
	Min temp								1.00	-038	0.53*	0.88*	0.19	0.18	0.36	-0.20	0.49*	0.71*	0.35
	Precip									1.00	-0.44	-0.44	0.55*	-0.26	-0.32	0.85*	-0.43	-0.49*	0.28
4	Max temp										1.00	0.76*	0.19	0.72*	0.55*	-0.44	0.98*	0.85*	0.52*
	Min temp											1.00	0.17	0.62*	0.71*	-0.41	0.78*	0.87*	0.49*
	Precip												1.00	0.04	0.06	-0.68*	0.17	0.21	0.87*
5	Max temp													1.00	0.77*	•0.49*	0.82*	0.59*	0.42
	Min temp														1.00	-0.52*	0.66*	0.77*	0.48*
	Precip															1.00	-0.49*	-0.48*	0.29
6	Max temp																1.00	0.86*	0.54*
	Mm temp																	1.00	0.57*
	Precip																		1.00

Notes: *Significant at *a* = 0.01.
Stage 1 = Planting to tassel initiation.
Stage 2 = Tassel initiation to ear initiation.
Stage 3 = Ear initiation to end of row set.
Stage 4 = End of row set to silk.
Stage 5 = Silk to end of lag phase.
Stage 6 = End of lag phase to maturity.

Table A14. Weather Variable Correlations at Different Growth Stages, Corn Planting Date Experiment

		Stage 1			*Stage 2*			*Stage 3*			*Stage 4*			*Stage 5*			*Stage 6*		
Stage	*Variable*	*Max temp*	*Min temp*	*Precip*	*Max temp*	*Min temp*	*Precip*	*Max temp*	*Min temp*	*Precip*	*Max temp*	*Min temp*	*Precip*	*Max temp*	*Min temp*	*Precip*	*Max temp*	*Min temp*	*Precip*
1	Max temp	1.00	0.97*	-0.54*	0.51*	0.76*	0.40	0.49*	0.72*	0.03	0.33	0.64*	-0.31	0.63*	0.18	-0.03	0.41	0.26	0.11
	Min temp		1.00	0.45*	0.70*	0.85*	0.54*	0.34	0.59*	-0.09	0.42	0.70*	-0.19	0.63*	0.29	-0.06	0.45*	0.30	0.15
	Precip			1.00	0.04	41.32	41.00	41.17	-0.37	0.10	0.48*	0.15	0.57*	0.17	0.56*	-0.04	0.17	0.331	0.62*
2	Max temp				1.00	0.82*	0.70*	-0.10	0.05	-0.31	0.61*	0.68*	0.15	0.49*	0.54*	-0.11	0.52*	0.43*	0.27
	Min temp					1.00	0.63*	0.22	0.32	-0.13	0.48*	0.70*	-0.16	0.52*	0.41	0.10	0.66*	0.52*	0.16
	Precip						1.00	•0.34	-0.17	-0. 10	0.23	0.29	0.52*	0.14	0.27	0.41	0.14	0.04	0.33
3	Max temp							1.00	0.91*	0.51*	0.35	0.56*	-0.55*	0.66*	0.16	•0.04	0.63*	0.62*	0.30
	Min temp								1.00	0.43	0.26	0.56*	-0.50*	0.65*	0.02	-0.07	0.47*	0.41	0.22
	Precip									1.00	-0.13	-0.00	0.11	0.05	-0.25	0.65*	0.15	0.17	0.49*
4	Max leap										1.00	0.91*	0.02	0.89*	0.96*	-0.34	0.79*	0.81*	0.60*
	Min temp											1.00	-0.17	0.96*	0.79*	-0.24	0.87*	0.84*	0.53*
													1.00	-0.20	0.11	0.45*	41.28	41.25	0.53*
3	Max temp													1.00	0.77*	-0.31	0.78*	0.77*	0.55*
	Mm temp														1.00	-0.32	0.69*	0.74*	0.55*
	Precip															1.00	-0.05	-0.10	0.34
6	Max temp																1.00	0.98*	0.48*
	Min temp																	1.00	0.53*
	Precip																		1.00

Notes: *Significant at α = 0.01.
Stage 1 = Planting to tassel initiation.
Stage 2 = Tassel initiation to ear initiation.
Stage 3 = Ear initiation to end of row set.
Stage 4 = End of row set to silk.
Stage 5 = Silk to end of lag phase.
Stage 6 = End of lag phase to maturity.

Table A15. Weather Variable Correlations at Different Growth Stages, Corn Open-Area Experiment

		Stage 1			*Stage 2*			*Stage 3*			*Stage 4*			*Stage 5*			*Stage 6*		
Stage	Variable	*Max temp*	*Min temp*	*Precip*	*Max temp*	*Min temp*	*Precip*	*Max temp*	*Min temp*	*Precip*	*Max temp*	*Min temp*	*Precip*	*Max temp*	*Min temp*	*Precip*	*Max temp*	*Min temp*	*Precip*
1	Max temp	1.00	0.19	-0.71*	0.68*	0.25	-0.18	0.65*	0.59*	-0.65*	0.38	0.57*	0.23	0.61*	-0.11	0.10	0.56*	0.22	-0.87*
	Min temp		1.00	0.12	-0.58	0.98*	0.38	-0.25	0.71*	-0.43	-0.66*	0.10	0.68*	-0.42	-0.37	-0.93*	-0.35	-0.13	0.23
	Precip			*1.00*	*-0.61**	*0.20*	*0.82**	-0.98*	*-0.60**	*-0.04*	*-0.81**	*-0.93**	*0.47**	*-0.94**	*-0.60**	*-0.35*	*-0.95**	-0.81*	*0.57**
2	Max temp				1.00	-0.49*	-0.34	0.65*	-0.09	-0.29	0.74*	0.31	-0.24	0.76*	0.08	0.76*	0.64*	0.17	-0.91*
	Min temp					1.00	0.54*	0.33	0.61*	-0.60*	0.73*	-0.04	0.82*	-0.48*	-0.55*	-0.91*	-0.44*	-0.31	0.11
	Precip						1.00	-0.86*	-0.32	-0.60*	-0.86*	-0.83*	0.87*	-0.84*	-0.94*	-0.48*	-0.90*	0.95*	0.11
3	Max temp							1.00	0.50*	-0.14	0.89*	0.91	-0.56*	0.98*	0.67*	0.47*	0.99*	0.84*	-0.55*
	Min temp								1.00	-0.21	0.06	0.77*	0.15	0.33	0.22	0.50*	0.42	0.54*	-0.13
	Precip									1.00	0.36	0.19*	-0.83*	0.15	0.81*	0.29	0.25	0.56*	0.62*
4	Max temp										1.00	0.67*	-0.79*	0.95*	0.73*	0.80*	0.93*	0.74*	-0.48*
	Min temp											1.00	-0.46*	0.82*	0.70*	4.12	0.89*	0.92*	-0.28
	Precip												1.00	-0.61*	-0.91*	-0.64*	-0.66*	-0.74*	-0.11
5	Max temp													1.00	0.65*	0.63*	0.99*	0.77*	-0.61*
	Mis temp														1.00	0.39	0.74*	0.93*	0.20
	Precip															1.00	0.55*	0.25	-0.44*
6	Max temp																1.00	0.86*	-0.50*
	Min temp																	1.00	-0.01
																			1.00

Notes: *Significant at $\alpha = 0.01$.
Stage 1 = Planting to tassel initiation.
Stage 2 = Tassel initiation to ear initiation.
Stage 3 = Ear initiation to end of row set.
Stage 4 = End of row set to silk.
Stage 5 = Silk to end of lag phase.
Stage 6 = End of lag phase to maturity.

Table A16. Weather Variable Correlations at Different Growth Stages, Soybean Mobile Shelter Experiment

		Stage 1			*Stage 2*			*Stage 3*			*Stage 4*		
Stage	*Variable*	*Max temp*	*Min temp*	*Precip*	*Max temp*	*Min temp*	*Precip*	*Max temp*	*Min temp*	*Precip*	*Max temp*	*Min temp*	*Precip*
1	Max temp	1.00	0.47*	-0.46	0.89*	0.39	-0.11	0.40	0.35	0.06	0.63	0.74*	-0.01
	Min temp		1.00	0.52*	0.45	0.84*	0.00	-0.27	0.99*	0.07	-0.24	-0.07	0.05
	Precip			1.00	-0.48*	0.30	-0.06	-0.51*	0.59*	0.09	-0.66*	-0.64*	0.12
2	Max temp				1.00	0.61*	0.29	0.02	0.39	0.01	0.36	0.61*	-0.08
	Min temp					1.00	0.45	-0.57*	0.88*	-0.01	-0.45	-0.16	-0.05
	Precip						1.00	-0.70*	0.08	0.29	-0.44	-0.17	0.20
3	Max temp							1.00	-0.39	0.06	0.77*	0.48*	0.10
	Min temp								1.00	0.05	-0.38	-0.20	0.04
	Precip									1.00	0.08	0.08	0.92*
4	Max temp										1.00	0.92*	0.02
	Min temp											1.00	-0.03
	Precip												1.00

Notes: Significant at $\alpha = 0.01$.
Stage 1 = Planting to 1st unifoliate.
Stage 2 = 1st unifoliate to floral induction.
Stage 3 = Floral induction to first flower.
Stage 4 = First flower to maturity.

Table A17. Weather Variable Correlations at Different Growth Stages, Soybean Open-Area Experiment

		Stage 1			*Stage 2*			*Stage 3*			*Stage 4*		
Stage	*Variable*	*Max temp*	*Min temp*	*Precip*	*Max temp*	*Min temp*	*Precip*	*Max temp*	*Min temp*	*Precip*	*Max temp*	*Min temp*	*Precip*
1	Max temp	1.00	0.35	-0.90*	0.88*	0.52*	-0.07	0.25*	0.16	-0.26	0.49	0.64*	0.50*
	Min temp		1.00	-0.02	0.37	0.96	0.56*	-0.82*	0.94*	0.58*	-0.53*	-0.17	0.64*
	Piecip			1.00	-0.62*	-0.15	0.02	-0.53*	0.07	0.59*	-0.54*	-0.50*	-0.10
2	Max temp				1.00	0.61*	-0.37	0.14	0.07	0.03	0.58*	0.84*	0.78*
	Min temp					1.00	0.34	-0.67*	0.82*	0.54*	-0.29	0.11	0.80*
	Precip						1.00	-0.62*	0.79*	0.19	-0.84*	-0.79*	-0.18
3	Max temp							1.00	-0.88*	-0.76*	0.85*	0.56*	-0.36
	Min temp								1.00	0.51*	-0.76*	-0.48*	0.37
	Precip									1.00	-0.47*	-0.19	0.58*
4	Max temp										1.00	0.91*	0.16
	Min temp											1.00	0.52*
	Precip												1.00

Notes: Significant at $\alpha = 0.01$.
Stage 1 = Planting to 1st unifoliate.
Stage 2 = 1st unifoliate to floral induction.
Stage 3 = Floral induction to first flower..
Stage 4 = First flower to maturity.

Table A18. Results of Analysis of Variance on Corn Yield Components, Vegetative Components, and Total Grain Yield

		Number of rows per ear		*Number of kernels per row*		*Cob dry weight*		*Vegetative dry weight*		*Mass of200 kernels*		*Total yield*	
	DF[1]	*MS[2]*	*Pr>F[3]*	*MS*	*Pr>F*	*MS*	*Pr>F*	*MS*	*Pr>F*	*MS*	*Pr>F*	*MS*	*Pr>F*
Year	4	47.6	0.0001	140.9	0.0018	483.5	0.0001	7,8195	0.0001	1,410.0	0.0001	72,381,380.0	0.0001
Rep (year)	10	*63*	0.0001	25.6	0.5317	13.5	0.0001	377.6	0.0001	27.1	0.0108	10,409,806.0	0.0001
Rainfall	5	5.4	0.0026	11.4	0.8438	12.2	0.0016	1,018.1	0.0001	26.7	0.0347	15,070,425.0	0.0001
Year rainfall	20	0.9	0.7613	47.8	0.0661	4.3	0.0847	90.3	0.1545	5.4	0.9395	1,771379.0	0.1896
Error	50	1.3		28.1		2.7		63.4		10.2		1305479.0	

Notes:
[1]DF = Degrees of freedom.
[2]MS = Mean square.
[3]Pr>F = Probability of a greater F statistic. An effect is significant if this value is < 0.10.

Table A19. Correlations Between the Yield Components and Weather Variables During Different Growth stages, Corn Mobile Shelter Experiment

Stage	*Variable*	*Number rows per ear*	*Number kernels per row*	*Cob dry weight*	*Vegetative dry weight*	*Number eared plants*	*Number barren plants*	*Mass of 200 kernels*	*Total yield*
Stage 1	Max temp	-0.86*	-0.23	-0.89*	-0.65*	0.20	0.71*	-0.54*	-0.56
	Min temp	-0.48*	-0.57*	-0.72*	-0.80*	0.14	0.44	-0.73*	-0.63*
	Precip	0.51*	-0.28	0.28	0.11	0.12	-0.19	-0.19	0.21
Stage 2	Max temp	-0.39	0.06	-0.28	-0.24	-0.30	-0.19	0.48*	-0.42
	Min temp	-0.53*	-0.57*	-0.75	-0.83*	0.13	0.41	-0.71*	-0.67*
	Precip	-0.30	-0.04	-0.33	0.14	0.13	-0.08	0.20	-0.18
Stage 3	Max temp	0.11	0.29	0.22	0.31	-0.28	-0.28	0.68*	0.13
	Min temp	-0.06	-0.35	-0.21	-0.43	-0.34	-0.31	0.22	-0.51*
	Precip	-0.02	-0.17	0.06	0.27	0.44	-0.00	-0.17	0.33
Stage 4	Max temp	-0.07	0.08	-0.04	0.02	-0.28	-0.16	0.49*	-0.12
	Min temp	-0.25	-0.32	-0.40	-0.45	-0.22	0.02	0.06	-0.49*
	Precip	0.36	-0.01	0.23	0.39	0.33	-0.37	0.26	0.39
Stage 5	Max temp	-0.51*	-0.07	-0.54*	-0.28	0.07	0.52*	-0.17	-0.25
	Min temp	-0.17	-0.25	-0.36	-0.22	0.09	0.48*	-0.33	-0.11
	Precip	0.29	0.05	0.25	0.33	0.33	-0.34	0.09	0.35
Stage 6	Max temp	-0.15	0.03	-0.15	-0.04	-0.20	0.00	0.35	-0.15
	Min temp	0.11	-0.12	-0.01	-0.03	-0.23	-0.11	0.28	-0.09
	Precip	0.23	-0.04	0.09	0.28	0.24	-0.17	0.19	0.29

Notes: *Significant at $\alpha = 0.01$.
Stage 1 - Planting to tassel initiation.
Stage 2 - Tassel initiation to ear initiation.
Stage 3 - Ear initiation to the end of row set.
Stage 4 - End of row set to silk.
Stage 5 - Silk to the end of the lag phase.
Stage 6 - End of lag phase to maturity.

Table A20. Yield Components with Significant Linear and Quadratic Responses to Weather Variables

		Number rows per ear		*Number kernels per row*		*Cob dry weight*		*Vegetative dry weight*		*Mass of 200 kernels*		*Total yield*	
Stage	*Variable*	*Linear* r^2	*Quadratic* R^2	*Linear* r^2	*Quadratic* R^2	*Linear* r^2	*Quadratic* R^2	*Linear* r^2	*Quadratic* R^2	*Linear* r^2	*Quadratic* R^2	*Linear* r^2	*Quadratic* R^2
1	Max temp	0.733	0.751	0.345		0.785		0.403		0.261	0.620	0.288	0.432
	Min temp	0.203	0.394			0.503	0.687	0.626	0.718	0.523	0.551	0.375	0.538
	Precip	0.096		0.102									
2	Max temp	0.119	0.533				0.639		0.722	0.204	0588	0.151	0.670
	Min temp	0.261	0.394	0.321		0.540	0.694	0.673	0.765	0-.504	0.559	0.433	0590
	Precip												
3	Max temp				0.154			0.086		0.442	0.469		
	Min temp		0530	0.093	0.245		0.758	0.156	0.794		0.654	0.235	0.627
	Precip												
4	Max temp									0.217	0.473		
	Min temp			0.074		0.131		0.177	0.347			0.212	0.430
	Precip											0.064	
5	Max temp					0.264	0.443						
	Min temp			0.213		0.128	0.415		0.380	0.079	0.826		0.108
	Precip											0.086	
6	Max temp									0.088	0.443		
	Min temp												0.112
	Precip												

Note: The coefficients of determination are the adjusted coefficients.
Stage 1 - Planting to tassel initiation.
Stage 2 - Tassel initiation to ear initiation.
Stage 3 - Ear initiation to the end of row set.
Stage 4 - End of row set to silk.
Stage 5 - Silk to the end of the lag phase.
Stage 6 - End of lag phase to maturity.

Table A21. Optimum Maximum and Minimum Temperatures for Corn Yield Components (°C)

Stage	*Weather variable*	*Number rows per ear*	*Number kernels per row*	*Cob dry weight*	*Vegetative dry weight*	*Mass of 200 kernels*	*Total yield*
1	Max temp					26.9	
	Min temp	13.8		13.2	12.4		13.4
2	Max temp						
	Min temp	16.2		15.9	15.6		16.0
3	Max temp						
	Min temp	17.9	17.8	17.9	17.9	18.0	17.8
4	Max temp						
	Min temp				18.0		18.0
5	Max temp			28.3			
	Min temp	17.7		17.7	17.8	17.8	17.8
6	Max temp						
	Min temp						14.7

Note: Values were determined from the significant quadratic responses of the yield components to the different weather variables.
Stage 1 - Planting to tassel initiation.
Stage 2 - Tassel initiation to ear initiation.
Stage 3 - Ear initiation to the end of row set
Stage 4 - End of row set to silk.
Stage 5 - Silk to the end of the lag phase.
Stage 6 - End of lag phase to maturity.

Table A22. Results of Analysis of Variance on Corn Yield Components, Vegetative Components, and Total Grain Yield, Planting Date Study

Main effects and interaction time	*Number of rows per ear*			*Number of kernels per row*		*Cob dry weight*		*Vegetative dry weight*		*Total yield*	
	DF[1]	*MS*[2]	*P4>F*[3]	*MS*	*Pr>F*	*MS*	*Pr>F*	*MS*	*Pr>F*	*MS*	*Pr>F*
Year(YR)	2	123.2	0.0001	23.3	03081	934.5	0.0001	7,229.7	0.0001	260,493,441.7	0.0001
Date of planting (DOP)	1	0.9	0.4532	848.6	0.0001	104.2	0.0001	4,214.4	0.0001	180,625,204.2	0.0001
YR DOP	2	22.0	0.0001	0.5	0.9728	36.4	0.0001	1,130.1	0.0001	10,408,102.5	0.0020
Population (POP)	1	49.1	0.0001	191.2	0.0022	820.1	0.0001	10,537.4	0.0001	82,757.6	0.8207
YR POP	2	1 5	03791	107.9	0.0050	12.0	0.0274	167.9	0.1206	94,760.7	0.9427
DOP POP	1	3.0	0.1679	97.3	0.0275	2.1	0.4207	1.7	0.8824	610,383.1	0.5384
YR DOP POP	2	0.1	0.9243	26.2	0.2670	1.4	0.6609	24.2	0.7344	303,344.7	0.8280
Rainfall (PPN)	5	9.1	0.0001	14.5	0.5970	25.9	0.0001	2,981.3	0.0001	29,937,722.2	0.0001
YR PPN	10	1.9	0.2812	20.4	0.4125	6.8	0.0286	62.2	0.6330	2,539,094.1	0.1175
DOP PPN	5	0.1	0.9966	12.3	0.6809	2.0	0.6882	91.6	0.3265	277,820.2	0.9722
YR DOP PPN	10	2.0	0.2511	15.2	0.6556	3.0	0.5094	87.0	03572	2,663,973.4	0.0958
POP PPN	5	2 3	0.2095	21.4	03684	5.9	0.1145	31.8	0.8434	689,499.7	0.8275
YR POP PPN	10	0.8	0.8841	14.6	0.6800	1.4	0.9238	24.7	0.9761	541,226.4	0.9696
DOP POP PPN	5	0.9	0.7174	10.4	0.7527	1.4	0.8180	35.9	0.8607	1,263,164.9	0.5607
YR DOP POP PPN	10	2.6	0.0901	40.2	0.0326	3.0	0.5125	29.2	0.9565	876,801.0	0.8547
Error	144	1.6		19.6		3.3		78.2		1,605,222.7	

Notes: [1]DF = Degrees of freedom.
[2]MS = Mean square.
[3]Pr>F = Probability of a greater F statistic An effect is significant if this value is < 0.10.

Table A23. Correlations Between Corn Yield Components and Weather Variables During Different Growth Stages, Planting Date Experiment

Stage	*Variable*	*Number rows per ear*	*Number kernels per row*	*Cob dry weight*	*Stover dry weight*	*Number eared plants*	*Number barren plants*	*Mass of 200 kernels*	*Total yield*
Stage 1	Max temp	-0.36	-0.54*	-0.80*	-0.30	-0.33	0.49*	-0.02	-0.83*
	Min temp	-0.50*	-0.43*	-0.84*	-0.43*	-0.34	0.47*	0.15	-0.84*
	Precip	0.41	055*	0.54*	0.21	0.27	-0.35	-0.54*	0.68*
Stage 2	Max temp	-0.68*	0.14	-0.68*	-0.69*	-0.25	0.32	0.49*	-0.53*
	Min temp	-0.64*	-0.16	-0.90*	-0.59*	-0.37	0.44*	-0.36	-0.77*
	Precip	-0.50*	-0.16	-0.41	-0.12	-0.03	0.07	0.40	-0.25
Stage 3	Max temp	038	-0.18	-0.35	-0.05	-0.07	0.11	0.75*	-0.33
	Min temp	0.19	-0.35	-0.50*	-0.11	-0.12	0.22	0.63*	-0.52*
	Precip	0.50*	0.01	0.09	0.47*	0.23	-0.21	-0.03	0.22
Stage 4	Max temp	-0.02	0.17	-0.32*	-0.37	-0.11	0.14	-0.13	-0.20
	Min temp	-0.14	0.00	-0.62*	-0.47*	-0.21	0.28	-0.17	-0.49*
	Precip	0.12	0.12	0.41	0.42	039	-0.39	-0.31	0.58*
Stage 5	Max temp	0.06	-0.10	-0.48*	-0.29	-0.15	0.23	-0.36	-0.41
	Min temp	0.03	0.19	-0.20	-0.28	-0.10	0.10	-0.18	-0.08
	Precip	0.12	-0.11	0.04	0.45*	0.29	-0.31	-0.03	0.24
Stage 6	Max temp	-0.07	0.19	-0.58*	-0.48*	-0.18	0.19	0.41	-0.38
	Min temp	0.06	0.29	-0.43*	-0.42	-0.11	0.11	0.26	-0.23
	Precip	0.40	0.10	0.06	0.25	0.33	-0.27	0.11	0.29

Notes: *Significant at $\alpha = 0.01$.
Stage 1 - Planting to tassel initiation.
Stage 2 - Tassel initiation to ear initiation.
Stage 3 - Ear initiation to the end of row set.
Stage 4 - End of row set to silk.
Stage 5 - Silk to the end of the lag phase.
Stage 6 - End of lag phase to maturity.

Table A24. Results of Analysis of Variance for Yield Components, Mobile Shelter Soybean Experiment

Main effects and interaction time		*Number of pods with beans*		*Number of pods without beans*		*Seed weight per pod*		*Dry vegetative weight*		*Total yield*	
	DF[1]	*MS*[1]	*Pr>F*[3]	*MS*	*Pr>F*	*MS*	*Pr>F*	*MS*	*Pr>F*	*MS*	*Pr>F*
Year	4	5,752.2	0.0001	161.9	0.0001	0.010	0.4200	137399.4	0.0001	1,218,763.8	0.0001
Rep(year)	10	160.2	0.0117	0.4	0.9485	0.013	0.2374	5,466.6	0.1327	209340.3	0.0329
Rainfall	5	226.6	0.0061	0.8	0.6113	0.027	0.0258	54,859.6	0.0001	694,916.1	0.0001
Year* rainfall	20	161.2	0.0027	0.4	0.9925	0.012	0.2426	8,9623	0.0029	186,271.7	0.0280
Error	50	60.8		1.2		0.010		3,407.2		95,073.8	

Notes: [1]DF = Degrees of freedom.
[2]MS = Mean square.
[3]Pr>F = Probability of a greater F statistic. An effect is significant if this value is < 0.10.

Table A25. Correlations Between Soybean Yield Components and Weather Variables during Different Growth Stages, Mobile Shelter Experiment

Stage	*Variable*	*Number pods with beans*	*Number pods without beans*	*Vegetative dry weight*	*Total yield*
1	Max temp	-036	-0.47*	0.04	-0.44
	Min temp	-030	-0.22	0.56*	0.18
	Precip	-0.19	-0.03	0.60*	0.58*
2	Max temp	-0.14	-0.15	-0.05	-036*
	Min temp	0.05	0.21	031	0.16
	Precip	0.42	0.58*	-0.04	0.23
3	Max temp	-0.15	-0.44	-0.22	-0.46
	Min temp	-0.21	-0.10	0.56*	0.25
	Precip	-0.05	-0.08	0.52*	0.42
4	Max temp	-0.49*	-0.71*	-0.16	-053*
	Min temp	-056*	-0.69*	-0.08	-0.49*
	Precip	0.05	-0.01	056*	0.50*

Notes: *Significant at $\alpha = 0.01$
Stage 1 = Planting to first unifoliate.
Stage 2 = Unifoliate to floral induction.
Stage 3 = Floral induction to first flower.
Stage 4 = First flower to maturity.

Table A26. Analysis of Variance on Corn Yield Components, Vegetative Components, and Total Grain Yield, Open-Area Experiment

Main effects and interaction terms		*Number of rows per ear*		*Number of kernels per row*		*Mass of 200 kernels*		*Total yield*	
	DF[1]	*MS*[1]	*Pr>F*[3]	*MS*	*Pr>F*	*MS*	*Pr>F*	*MS*	*Pr>F*
Year	2	1593	0.0001	659.1	0.0001	1,739.2	0.0009	376,441,550.6	0.0001
Rep(year)	6	3.9	0.0180	41.8	0.0040	6.6	0.7124	4330,535.1	0.0255
Rainfall	9	1.2	0.0932	9.0	03608	32.4	0.1923	1,514,344.7	0.1039
Year rainfall	18	0.9	0.1213	14.9	0.0172	20.9	03159	1,883,827.8	0.0769
Rainfall rep(year)	51	1.0	0.1102	16.5	0.0145	15.1	0.4403	988,375.6	0.1756
Error	3	0.1		0.8		105		287,695.6	

Notes: This analysis of variance includes ten water treatments.
[1]DF = Degrees of freedom
[2]MS = Mean square
[3]Pr>F = Probability of a greater F statistic. An effect is significant if this value is < 0.10.

Table A27. Analysis of Variance on Corn Yield Components, Vegetative Components, and Total Grain Yield, Open-Area Experiment, 1988-1991

Main effects and interaction terms		*Number of rows per ear*		*Number of kennels per row*		*Mass of 200 kernels*		*Total yield*	
	DF[1]	*MS*[2]	*Pr>F*[3]	*MS*	*Pr>F*	*MS*	*Pr>F*	*MS*	*Pr>F*
Year	3	53.5	0.0001	1455	0.0007	2070.0	0.0006	148,914,151.3	0.0002
Rep(year)	8	0.8	0.1397	30.7	0.0062	9.8	0.5886	1,252,795.0	0.1323
Rainfall	3	*12*	0.0964	13.3	0.0227	23.9	0.2594	1,818,279.3	0.0860
Year rainfall	9	0.7	0.1611	6.0	0.0636	17.4	03718	1399,419.9	0.1149
Rainfall rep(year)	21	0.9	0.1358	193	0.0117	4.6	0.8909	814,753.1	0.2213
Error	3	0.2		0.8		*105*		297,695.6	

Notes: This analysis of variance includes only the first four of the ten water treatments.
[1]DF = Degrees of freedom
[2]MS = Mean square
[3]Pr>F = Probability of a greater F statistic. An effect is significant if this value is < 0.10.

Table A28. Mean Corn Yield Components and Total Yield According to Year and Water Treatments, Open-Area Study, 1988-1991

Year	Water treatment	Number of rows/ear	Number of kernels/row	Kernel mass (g)	Cob dry weight (g/plant)	Vegetative dry weight (g/plant)	Grain yield (kg/ha)
1988	1	10.4 a	39.7 a	0.368 a			6,262 a
	2	12.0 a	32.8 a	0.341 ab			6,061 a
	3	10.9 a	35.5 a	0.349 ab			6,927 a
	4	125 a	37.3 a	0.317 ab			8,424 a
	5	12.0 a	36..4 a	0.335 ab			8,271 a
	6	10.7 a	31.1 a	0.353 ab			6,022 a
	7	13.0 a	33.6 a	0.304 b			7,834 a
	8	11.2 a	29.2 a	0.320 ab			6514 a
	9	12.4 a	35.6 a	0.317 ab			8,431 a
	10	12.4 a	33.2 a	0.325 ab			8,045 a
1989	1	16.0 a	43.6 a	0.324 bc	295 ab	94.6 ab	14,412 abc
	2	16.1 a	40.6 a	0.318 bc	26.9 ab	91.5 ab	13,491 abc
	3	16.6 a	42.8 a	0.336 ab	29.8 a	1003 a	15382 a
	4	16.2 a	40.9 a	0.326 bc	28.2 ab	75.2 b	13,936 bc
	5	16.6 a	40.8 a	0.332 abc	28.8 ab	93.3 ab	14,370 abc
	6	16.3 a	42.2 a	0.333 abc	29.0 ab	84.5 ab	14,355 abc
	7	16.7 a	39.6 a	0.305 c	26.0 b	74.8 b	13,232 c
	8	15.7 a	44.4 a	0.355 a	30.2 a	94.6 ab	14,723 ab
	9	15.9 a	413 a	0.321 be	27.8 ab	91.3 ab	13,718 bc
	10	15.6 a	43.9 a	0.343 ab	28.4 ab	93.9 ab	14,140 abc
1990	1	15.1 abc	43.0 a	0.269 a	25.0 a	68.1 a	12535 a
	2	14.6 c	42.4 a	0.261 a	22.2 a	71.7 a	11,087 a
	3	14.7 bc	41.8 a	0.269 a	22.8 a	73.9 a	11,229 a
	4	15.0 abc	42.3 a	0.266 a	23.3 a	71.8 a	12,098 a
	5	15.5 ab	41.7 a	0.264 a	22.2 a	66.5 a	11,729 a
	6	15.2 abc	44.4 a	0.263 a	23.2 a	65.4 a	12,153 a
	7	15.5 a	43.8 a	0.257 a	23.8 a	68.6 a	12,484 a
	8	15.4 a	43.9 a	0.264 a	25.2 a	75.3 a	12,938 a
	9	15.1 abc	43.8 a	0.270 a	24.0 a	70.4 a	12336 a
	10	15.0 abc	44.0 a	0.269 a	23.5 a	73.2 a	12,664 a
1991	1	15.4 b	35.9 a	0.204 a	14.7 a	64.0 a	7,581 a
	2	15.1 b	36.1 a	0.201 a	14.7 a	62.5 a	7507 a
	3	14.4 b	35.8 a	0.193 a	14.1 a	55.3 a	7,331 a
	4	15.9 a	36.1 a	0.196 a	15.00 a	60.7 a	7,432 a

Note: Means with same letter are not significantly different at $\alpha = 0.05$.
Precipitation treatments:
1. Natural rainfall.
2. Increase all daily rains 10 percent
3. Increase all daily rains 25 percent
4. Increase all daily rains 40 percent
5. Increase all daily rains of 254 mm to 25.4 mm by 10 percent (moderate rain).
6. Increase all daily rains of 254 mm to 25.4 mm by 25 percent (moderate rain).
7. Increase all daily rains of 254 mm to 25.4 mm by 40 percent (moderate rain).
8. Increase all daily rains above 25.4 mm by 10 percent (heavy rain).
9. Increase all daily rains above 25.4 mm by 40 percent (heavy rain).
10. Increase all daily rains less than 254 mm by 40 percent (light rain).

Table A29. Correlations Between Corn Yield Components and Weather Variables, Open-Area Experiment

Stage	*Variable*	*Number rows per ear*	*Number kernels per row*	*Cob dry weight*	*Stover dry weight*	*Number eared plants*	*Number barren plants*	*Mass of 200 kernels*	*Total yield*
1	Max temp	-059*	-0.73*	-0.98*	-0.81*	-034	038	-0.43	-0.93*
	Min temp	0.60*	0.29	-0.98*	-0.81*	0.45*	-0.49*	-0.91*	0.12
	Piecip	050*	0.81*	053*	0.18	037	0.40	053*	0.75*
2	Max temp	-0.95*	-0.78*	-0.88*	-0.89*	-0.62*	0.68*	-0.88*	-0.85*
	Min temp	050*	0.29	-0.93*	-0.88*	0.41	0.44*	-0.95*	0.06
	Piecip	0.26	057*	-0.12	-0.42	0.27	-0.28	0.12	031
3	Max temp	-055*	-0.83*	-0.43	-0.06	-0.41*	-0.44*	-0.43	•0.73*
	Min temp	0.19	-032	-0.79*	-0.47*	0.13	-0.14	0.79*	-037*
	Precip	0.28	0.13	0.73*	0.82*	0.07	-0.09	0.73*	0.49*
4	Max temp	-0.67*	-0.76*	0.17	0.47*	-0.52*	0.55*	0.16	-0.59*
	Min temp	-0.20	-0.66*	-0.45*	-0.08	•0.19	0.20	-0.45	-055*
	Precip	0.21	032	-0.62*	-0.78*	0.25	-0.25	-0.62*	-0.01
5	Max temp	-0.67*	-0.85*	-0.35	0.02	-0.49*	0.53*	-035	-0.75*
	Min temp	-0.02	-034	-0.32	0.59	0.13	-0.13	0.13	-0.02
	Precip	-0.73*	-051*	0.92*	0.74*	-052*	0.59*	-0.92*	-0.37
6	Max temp	-0.55*	-0.81*	-0.28	0.09	-0.42	0.45*	-0.28	-0.67*
	Min temp	-0.08	-0.52*	-0.06	0.29	-0.15	0.15	-0.06	-0.28
	Precip	0.87*	0.72*	0.86*	0.80*	0.51*	-0.56*	0.86*	0.92*

Notes: *Significant at a = 0.01.
Stage 1 - Planting to tassel initiation.
Stage 2 - Tassel initiation to ear initiation.
Stage 3 - Ear initiation to the end of row set
Stage 4 - End of row set to silk.
Stage 5 - Silk to the end of the lag phase.
Stage 6 - End of lag phase to maturity.

Table A30. Results of Analysis of Variance on Pod Numbers, Vegetative Mass, and Total Grain Yield, Open-Area Soybean Study

Main effects and interaction terms		*Number of pods with beans*		*Number' of pods without beans*		*Seed wetight per pod*		*Dry vegetative weight*		*Total yield*	
	DF[1]	*MS*[2]	*Pr>F*[3]	*MS*	*Pr>F*	*MS*	*Pr>F*	*MS*	*Pr>F*	*MS*	*Pr>F*
Year	3	3,552.6	0.0001	12.5	0.0001	0.099	0.0001	331326.1	0.0001	15473,2605	0.0001
Rep(year)	8	63.5	0.2808	0.4	03516	0.002	0.8566	4,296.8	0.0364	138,352.4	0.1377
Rainfall	3	108.6	0.0363	0.4	0.3538	0.004	03709	1,100.4	0.8206	115,934.7	0.2286
Year rainfall	9	75.7	0.0907	0.4	0.7490	0.004	0.4677	2,261.4	0.3003	110,435.3	0.2006
Rainfall rep(year)	27	50.6		0.3		0.004		1,944.8		86,062.0	
Error	72			0.4							

Notes: [1]DF = Degrees of freedom
[2]MS = Mean square
[3]Pr>F = Probability of a greater F statistic An effect is significant if this value is < 0.10.

Table A31. Correlations between Soybean Yield Components and Weather Variables, Open-Area Experiment

Stage	*Variable*	*Number pods with beans*	*Number pods without beans*	*Vegetative dry weight*	*Total yield*
1	Max temp	0.03	0.27	-0.85*	-0.96*
	Min temp	-0.10	0.13	-0.54*	-031
	Precip	-035	-0.49*	0.80*	0.88*
2	Max temp	-0.39	-0.15	-0.59*	-0.82*
	Min temp	-0.29	0.02	-0.59*	-0.47*
	Precip	052*	0.66*	-0.40	0.04
3	Max temp	0.18	0.03	0.04	-0.26
	Min temp	0.08	032	-0.49*	-0.14
	Precip	-052*	-036	0.22	030
4	Max temp	-0.23*	-0.27	-0.05	-0.47*
	Min temp	-0.46*	-038	-0.19	-059*
	Precip	-0.64*	-034	-031	-0.45*

Note: *Significant at $\alpha = 0.01$
Stage 1 = Planting to first unifoliate.
Stage 2 = Unifoliate to floral induction.
Stage 3 = Floral induction to first flower.
Stage 4 = First flower to maturity.

Table A32. Ranks of Average Corn Yields According to Rain Treatment, Open-Area Plots

Treatment	*Three-year study (kg/ha)*[1]	*Four-year study (kg/ha)*[2]
10	11,616	-
9	11,495	-
4	11,486	10,550
5	11,457	-
8	11392	-
3	11,199	10,205
7	11,183	-
1	11,070	10,198
6	10,843	-
2	10,213	9,536

Notes: [1]Based on 1988-1990.
[2]Based on 1988-1991.
Precipitation treatments:
1. Natural rainfall.
2. Increase all daily rains 10 percent
3. Increase all daily rains 25 percent
4. Increase all daily rains 40 percent
5. Increase all daily rains of 2.54 mm to 25.4 mm by 10 percent (moderate rain).
6. Increase all daily rains of 2.54 mm to 25.4 mm by 25 percent (moderate rain).
7. Increase all daily rains of 2.54 mm to 25.4 mm by 40 percent (moderate rain).
8. Increase all daily rains above 25.4 mm by 10 percent (heavy rain).
9. Increase all daily rains above 25.4 mm by 40 percent (heavy rain).
10. Increase all daily rains less than 2.54 mm by 40 percent (light rain).

Table A33. Ranks of Average Soybean Yields According to Rain Treatments, Open-Area Plots

Treatment	*Kg/ha*
1	2,535
3	2,529
7	2,459
5	2,432
9	2,411
4	2383
10	2,382
6	2,297
2	2,296
8	2,240

Notes: Precipitation treatments:

1. Natural rainfall.
2. Increase all daily rains 10 percent
3. Increase all daily rains 25 percent
4. Increase all daily rains 40 percent
5. Increase all daily rains of 254 mm to 25.4 mm by 10 percent (moderate rain).
6. Increase all daily rains of 254 mm to 25.4 mm by 25 percent (moderate rain).
7. Increase all daily rains of 254 mm to 25.4 mm by 40 percent (moderate rain).
8. Increase all daily rains above 25.4 mm by 10 percent (heavy rain).
9. Increase all daily rains above 25.4 mm by 40 percent (heavy rain).
10. Increase all daily rains less than 254 mm by 40 percent (light rain).