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USE OF UNIQUE FIELD FACILITIES TO SIMULATE EFFECTS OF ENHANCED RAINFALL ON CROP PRODUCTION

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1. INTRODUCTION

The major goal of the weather modification research in Illinois has been to develop a technology in rainfall enhancement that would result in increased Illinois crop yields and a reduction in the year-to-year variations of crop yield (Changnon, 1986). Much of what has been assessed about the value of added water on crop yields in Illinois has come from the use of crop yield-weather models based on historical records of yields and past weather conditions (Garcia et al., 1987). The actual rainfall amounts have been used as inputs to regression type models and the predicted yields with the effects of additional rainfall compared to those yields estimated with natural rainfall. The model results point to the importance of summer weather conditions, particularly the July and August rainfall. However, the basis of their computation and the related assumptions leave the prediction of yield increases apt to be obtained too uncertain. Thus, actual field experiments are needed to evaluate and quantify the effects of differing amounts of additional rainfall on crop yields.

In the spring of 1987, recently constructed "rain shelters" became available in which field experiments of rain effects on crops could be conducted. Some shelters were designed to be moved over the test plot area during a rain event to exclude natural rain. When there was no precipitation falling, the shelters could be moved off the plots so the plants experienced the same weather as other crops in the region. An overhead sprinkler irrigation system was installed in the shelters so the time, amount, and quality of water applied to each plot could be controlled. This system allowed for the establishment of an experimental design to begin to test the validity of the crop-weather model results in an actual field situation. This paper addresses the 1987 field experiment, the facility, the rain models used, and the yield results.

2. EXPERIMENTAL METHOD

A multi-year field experiment was established in the spring of 1987 to determine the effects of augmentation of natural rainfall through rain increases on crop yields. Two shelters, one movable and the other stationary, were used in the 1987 experiment. The stationary shelter was left open so that natural (1987) rainfall could reach the crop and soil, and was fitted with a suspended overhead sprinkler irrigation system that allowed the application of additional water on each plot. The sprinkler nozzles were raised as the crop grew so that the database between the sprinklers and the top of the crop was 1.2 m. The plots in the stationary open shelter were treated with predetermined amounts of water added to the actual 1987 daily rainfall.

The water treatments in the movable shelter were designed to test the effects of added rain during a typical dry summer, a typical average rainfall summer, and a typical wet summer. The 1987 experiment will be replicated in 1988 and other growing seasons. The 1987 water additions began 1 June and ended on 31 August.

Corn (a Mo17 x B73 Cross) and soybeans (a Williams variety) were planted in the stationary (open) and mobile (covered) shelters on 28 May 1987. Prior to planting the corn, 341 kg ha^{-1} of nitrogen, 94 kg ha^{-1} of potassium, and 94 kg ha^{-1} of phosphorus were applied. The corn was planted in a 0.76 m spaced rows at a population of 64,220 plants ha^{-1}. The soybeans were planted with the same row spacing as the corn with a plant density of 430,000 plants ha^{-1}. The plots are both situated on a Drummer silty clay loam soil (fine-silty mixed mesic Typic Haplaquolls), a naturally poorly drained soil that had been artificially drained. These conditions are typical of those found through much of Illinois. The plots are located in east central Illinois on the University of Illinois Agricultural Experiment Farms at Urbana. The shelters were provided by the University of Illinois Agronomy Department.

3. FACILITIES

3.1 Stationary Shelter

The stationary shelter was an aluminum framework supporting a series of controllable nozzles, each centered over a 3x3 meter plot. The amount of water going to each of 6 plots could be individually controlled.

Ten different rainfall treatments were replicated three times. The ten treatments, consisted of additional water applied to various plots after each rain event. The water was totally deionized, and then ions added to make the water match that local rainwater. The additional rain increments were applied in the morning after determining the previous day's rainfall at 0700. Figure 1 shows a map of the field plots and the ten treatments.

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S - 1	S - 7	S - 6	C - 1	C - 4	C - 1
S - 3	S - 7	S - 4	C - 9	C - 5	C - 8
S - 10	S - 4	S - 3	C - 1	C - 3	C - 7
S - 5	S - 2	S - 5	C - 3	C - 7	C - 9
S - 3	S - 6	S - 1	C - 2	C - 2	C - 10
S - 10	S - 7	S - 6	C - 9	C - 5	C - 5
S - 9	S - 2	S - 8	C - 3	C - 2	C - 7
S - 1	S - 9	S - 10	C - 4	C - 10	C - 4
S - 2	S - 4	S - 9	C - 6	C - 6	C - 10
S - 5	S - 8	S - 8	C - 8	C - 6	C - 8

1 = Natural Rainfall for 1987
2 = Increase all daily rains 10%
3 = Increase all daily rains 25%
4 = Increase all daily rains 40%
5 = Increase all daily rains of 0.254 cm to 2.54 cm by 10%
6 = Increase all daily rains of 0.254 cm to 2.54 cm by 25%
7= Increase all daily rains of 0.254 cm to 2.54 cm by 40%
8 = Increase all daily rains above 2.54 cm by 10%
9 = Increase all daily rains above 2.54 cm by 40%
10 = Increase all daily rains less than 0.254 cm by 40%

a. Test plots for the stationary (uncovered) experiments

C - 5	C - 2	C - 2
C - 2	C - 6	S - 1
C - 1	C - 5	C - 5
C - 3	C - 3	C - 4
C - 4	C - 1	C - 6
C - 6	C - 4	C - 3
S - 6	S - 3	S - 2
S - 1	S - 5	S - 5
S - 5	S -6	S - 4
S - 3	S - 2	S - 6
S - 2	S - 1	S - 1
S - 4	S - 4	S - 3

1 = Normal Rainfall
2 = Normal Rainfall plus 25%
3 = Typical Dry Year
4 = Typical Dry Year plus 25%
5 = Typical Wet Year
6 = Typical Wet Year plus 25%

b. Test plots for the mobile (covered) experiments

Figure 1. Patterns of field plots.

3.2 Mobile Shelter Experiment

The mobile shelter consisted of an aluminum frame covered by plastic with a suspended sprinkler system. The shelter was mounted on a track and moved on or off the test plots by a motor triggered by an automatic rain switch. By this means, all natural rainfall was excluded from the plots. The area covered was 10 by 40 meters and contained 36 test plots (each 3x3 m), each with individually controlled sprinkler nozzles centered over the plot. Figure 1 is a diagram of the plots in the shelter. Figure 2 presents photographs of the nozzles and the soybean planted portions of the shelter. The experiments conducted here studied the effects of altered rain level, applied to represent the effects of a typical average summer, a typical wet summer, and a typical dry summer, on crop yields. The typical average, wet, and dry summer were based on historical climate values from Urbana, Illinois. Water applications were conducted at times specified in the models developed using historical precipitation data. The water applications to simulate added rainfall due to weather modification were 25% more than the daily amount designated in the models.

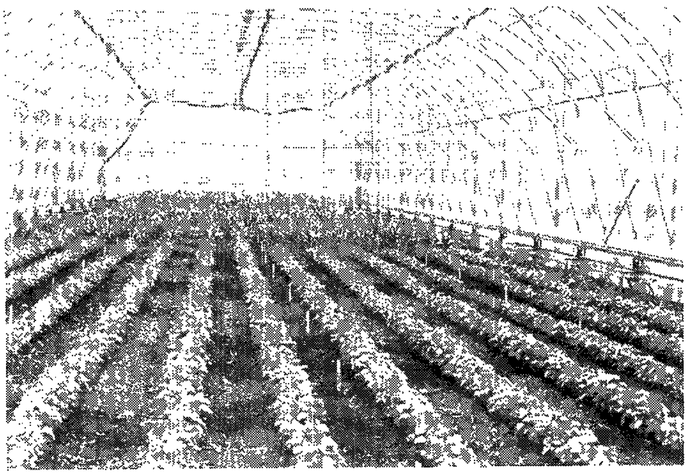
4. SUMMER RAINFALL MODELS

The typical summer seasons were designed using the long-term (1888-1986) average values of rainfall for June, July and August; the statistical distribution of rain days for each month; and the temporal distribution of rain days and rain amounts for each month. The results of this climatic design became "summer (Jun-Aug) rain models" for (1) an "average" summer, (2) a typical "wet" summer, and (3) a typical "dry" summer. Each summer type was defined using the data for the 18 wettest summers, the 18 driest summers, and the 18 summers having rain values nearest the 99-year average at Urbana. The monthly values selected for composing the wet, the near average, and the dry summers were based on the probability distributions of monthly rain values (Changnon, 1959).

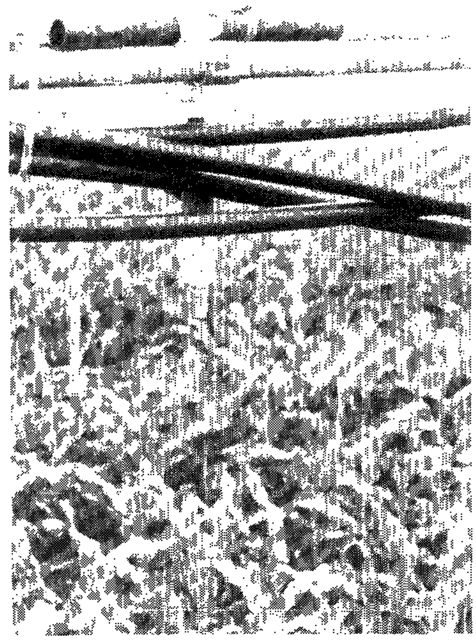
The frequency distributions of rain days during each type of summer were determined by analysis of the monthly frequencies in the 1888-1986 Urbana climate record. The resulting average frequencies of rain days for the wet, average, and dry summers are presented in Table 1.

4.1 Average Summer Model Calculations.

The daily rain day distributions for 0.254 mm (0.01 inch) increments were the basis for calculating the actual amounts for the average summer conditions. As shown in table 1, an "average summer" in Urbana has 26 days of $\geq$0.254 mm of rain. The frequency distributions show that 40% of these days, or 10



Covered shelter with soybean plots



Nozzle used to apply water to 3x3 meter test plots in both shelters

Figure 2. Field facilities.

Table 1. Rain day frequencies for Urbana, Illinois, 1901-1985

Summer Month	≥0.254 mm Wet	Avg	Dry	≥6.35 mm Wet	Avg	Dry	≥12.7 mm Wet	Avg	Dry	≥22.8 mm Wet	Avg	Dry
June	12	10	10	7	5	4	5	3	2	2	1	1
July	10	8	7	5	4	3	3	2	1	2	1	0
August	10	8	7	4	3	2	3	2	1	1	1	1
TOTALS	32	26	24	16	12	9	11	7	4	5	3	2

(Days with Rainfall)

rain days, were composed of values between 0.254 (0.01 inch) and 2.54 mm (0.1 inch). In this latter category, ten evenly distributed values were selected for insertion in the "average" summer rain model, with values ranging from 0.254 up to 2.54 mm.

These ten values were then distributed amongst the three summer months according to the magnitude of the 0.254 mm values (table 1), such that 4 rain days in this category were assigned to June, 3 to July, and 3 to August.

The amounts assigned within each month were decided based on the magnitude of the average monthly rainfall amounts. That is, the June average is 101.6 mm which is 36% of the summer total of 279.4 mm; the July average was 86.36 mm which is 31%; and the August average was 91.44 mm which is 33%. The sum of the 10 values was 15.24 mm, and application of the June percentage (36) to this resulted in 5.588 mm. Four rainfall values from the 10 were selected so that their sum approximated 5.588 mm. The values selected were 0.508, 0.762, 1.778, and 2.54 mm. This process was then repeated for the days in July and August.

A similar approach was used for determining and assigning heavier rainfalls for each of the 2.54 mm rain day categories (and the average summer). The 2.794 to 5.08 mm daily rain events represented 13% of all rain days, and three rain days were assigned to this category for the summer (1 in June, 1 in July, and 1 in August). Three days (1 each month) were also assigned to the 5.334 to 7.6 mm category.

Each of the 2.54-mm categories from 7.62 mm up through 22.8 mm averaged one rain day during the summer. The rain amount chosen and assigned to each of the rain categories was in the middle of the range (i.e., 8.8 mm for the 7.8 to 10.1 mm range). The six largest values were distributed with 2 assigned in June, 2 in July, and 2 in August. The distribution was such that each month received approximately 33 mm of total rainfall from these days. The final moderately heavy rain day values selected were 15.4 and 17.7 mm for June; 8.8 and 22.8 mm for July; and 12.4 and 21.5 mm for August.

The average summer also has three rain days with ≥22.8 mm, and these were assigned one to each month. Their magnitude in each month was established by summing all the other daily values already assigned, and subtracting those totals from the monthly average total. For example, in June, the 9 daily rain values less than 22.8 mm already selected totaled 58.2 mm. The difference between this value and the monthly mean of 101.6 mm for June is 43.4 mm; therefore, the greater than '22.8 mm' value used for June was 43.4 mm.

All rain days thus selected for each month were then distributed at dates using available climatic information. Feyerherm et al. (1966) showed that 50% of all summer rain days in central Illinois are followed by another rain day, but that the likelihood of 3 days of rain in a sequence is extremely small, less than 6%. Therefore, half of the summer rain days were "coupled" so that there would be two rain days in a row. For example, half of the rain days in June (6 of the 10) were used to form 3 pairs of rain days. Furthermore, each pair formed consisted of a relatively high and a moderately low rain value since past Urbana rain data (1951-70) revealed that 91% of such paired daily values differed by 50% or more.

The final temporal distribution of rain days throughout each month was based on 85-year amounts of rain per date and on probabilities of dry periods (Changnon, 1959). These provided information as to which dates of each month were apt to be in the wet or dry periods. The "wetter" summer periods included 8-15 June, 23-28 June, 2-5 July, and 10-19 August. The daily rain amounts selected were concentrated in these 'more likely' rain periods. For example, there are 10 days with 0.254 mm or more rain in June in an "average summer"; and, seven of these days were distributed within the two June 'wetter' periods. Two of the 8 July rain days were put in the 2-5 July period, and 4 of the 8 measurable rain days in August were distributed within the 9-day period of 10 to 18 August. The remaining rain days in each month were then randomly distributed amongst the other parts of each month, but such that no rainless period persisted for more than 7 days (an event with a low probability, <7%, for summer).

4.2 Wet and Dry Summer Rain Models

The rain-day distributions (by calendar dates) for the dry and wet summers were much the same as that set for the average summer. The magnitudes of rainfall on a rain day were adjusted for the wet and dry summers to match monthly averages, but not the rain dates; however, certain rain days identified in the average summer were deleted in the dry summer, and some days were added in the wet summer to conform to the values shown in table 1.

The amount of rain assigned to each rain day was determined by: 1) using the average monthly rainfall in wet and dry summers; and 2) using the rain day frequencies (table 1) to guide adjustments of the average summer daily values already selected. The mean June, July, and August rainfalls in the wet and dry summers were obtained from frequency curves (Changnon, 1959). These showed that the 20% frequency level (the wettest 18 years), a dry June had 70% of the June average rainfall, and a 20%-level wet June had 137% of the average rainfall.

The average of the rain day frequencies for the four rainfall levels shown in table 1 were used to determine the daily rainfall values. For example, table 1 shows that a July in a typical dry summer has one less rain day at the 0.254 mm level than the average. Therefore, one rain day already selected for the average July had to be deleted.

The rain-day level frequencies in table 1 reveal that the one day with ≥25.4 mm (1 inch) of rain in the average July does not occur in a dry July; hence the value of 39.878 mm rainfall assigned to 5 July in the average summer was reduced to 20.320 mm. In a like manner, the amounts of daily rainfall in the dry summer were adjusted downward to conform to match the average statistical distributions, and so that their sums matched the dry summer monthly values.

The rainfall values for months in wet summers were constructed from the average values in a similar fashion. The goal was to ensure that the adjusted values equaled the daily frequencies for the wet summer months shown in table 1, and that their totals matched the monthly totals for the wet summer. Many of the adjustments of average daily rainfall were to the heavier daily rainfall amounts, particularly those greater than 12.7 mm per day.

Finally, the rate of rainfall, the time of day that the rainfall occurred, and the duration of the rainfall event had to be specified. The control system for applying water prohibited variations of rain rates during a "rain period." Thus, the water application on a day with 8.128 mm rainfall had to be applied at a fixed rate. Further, the duration of the rain event had to be long enough to apply the specified amount of rain. In the case of the very heavy rain events in the covered shelter, and to prevent the "rain" from running off a plot onto an adjacent plot receiving less rainfall, it was necessary to divide the event into several smaller events on the same day.

The time of day of the 'rain event' was determined from an analysis of the diurnal distribution of summer rains (Huff, 1971). In general, this showed that between the hours of 0900 LST and 1400, each hour received 3% of the rain; between 1400 and 2000 each hour receives approximately 4%; and between 2000 and 0900 each hour receives about 5% of the total rain. This reflects the nocturnal maximum and morning minimum of Illinois.

Since we did not have the personnel to distribute water at all times of the day, a schedule involving three different times of application distributed across a sequence of six rain days was used to emulate nature. The prescribed water amount was applied in the hours between 1500 and 2000, and beginning at 1500, on the first and third 'rain day' of the 6-day sequence (which began on 1 June). On the second, fourth, and fifth 'rain days' of the sequence, the prescribed water values were applied between 0600 and 1500. After the initial sequence was done, it was repeated on the next 6 rain days, and continued through the summer. This scheme put 50% of the rain time in the nocturnal maximum, 33% in the late afternoon (lesser peak), and 17% in the mid-day minimum, a distribution that fit the local climatology.

5. FIELD RESULTS FOR 1987

Crop yields were determined by harvesting the center two rows of each plot. For corn, the ears were weighed, adjusting the weight to 15.5% moisture, and then calculating the yield. The yield components of the harvested soybean crop that were recorded are: (1) number of plants harvested; (2) number of pods per plant; (3) number of pods with at least one seed greater than 5 mm in diameter; (4) number of seeds per plant; and (5) the average weight of each seed. The yield was determined on a weight and moisture adjustment.

Treatments (added rainfall) in the shelters were started on schedule. The corn and soybean crop had just emerged by 1 June. During the vegetative stage of growth (June), the weather was unusually hot and dry. Differences in heights of the plants in the different treatments were easily observed and series of photographs were taken at several intervals.

Problems Developed. On 30 July a once in 100-year rainfall (114.3 mm) occurred in a 4-hour period. At the time of the storm, the movable shelter was over the plots (as scheduled) and no rain fell on the plots. However, due to the excessive rainfall rate and the level lay of the land, the plots were exposed to added surface runoff for approximately 3 hours. The soil moisture profiles of all plots were measured and found to be recharged. (At the time of this storm the corn was silking and the soybeans were beginning to flower.) Thus, during the critical corn growth stage of flowering, the "dry summer" plots were recovering from any stress they had been exposed to. Soil moisture measurements after the storm allowed estimation of the "water application" received by the flood, and this value was used to halt planned daily water applications scheduled for 4 days in the 30 July to 9 August period. During this interval, all water was excluded from the movable shelter.

The stationary (open shelter) experienced severe lodging problems at the end of July, which were caused by several factors. These included the 337 kg ha^{-1} of nitrogen, in addition to the residual nitrogen from three prior years of soybeans on these plots, plus the late May planting date and reduced light intensity caused by partial shading of the crop by the infrastructure of the stationary shelter. These caused the corn plants to grow taller than normal without additional thickening of the stem resulting in a weaker plant. Consequently, some plants were blown over by storm downdrafts at the end of July and this limited the corn results. The soybean plots in the stationary shelter did not experience any problems, and the results from these open plots are usable.

Relevant to the 1987 yield outcomes were the other (uncontrolled) weather conditions in 1987. The spring season (Mar-May) was unseasonably warm and dry providing some early moisture stress conditions in June. June itself had above normal (+3°F) temperatures and was relatively dry until late in the month when rain produced an above normal total. July and August had near normal temperatures and both had above normal rainfall. The 3-month (Jun-Aug) total experienced in the open shelter plots was 17.84 inches (45.2 cm) which is 6.9 inches or 162% above normal, truly a very wet summer.

The soybean and corn yields in the covered shelter plots, and the soybean yields from the open shelter are summarized in table 2. Each rainfall treatment was made on 3 randomly selected plots, and the yield values shown are the averages of the 3 plots with comparable treatment. Also shown in table 2 is the total rain (water) applied in the 3 summer months (Jun-Aug) to the covered plots, and to the open shelter plots.

Table 2. The soybean and corn yields from the experimental plots and their associated rainfall (water) applications.

Rainfall Treatment	Covered Plots		
	Rainfall, mm	Soybean Yield, bu/acre	Corn Yield, bu/acre
Dry summer	160.00	43.7	79.3
Dry +25%	200.66	45.4	76.2
Average summer	278.56	48.0	70.6
Average +25%	345.44	47.9	87.6
Wet summer	381.08	44.9	106.1
Wet +25%	474.98	47.3	98.7

Rainfall Treatment	Open Plots - Soybeans	
	Rainfall, mm	Yield, bu/acre
Actual Rain	452.1	32.7
Actual +10%	497.8	26.1
Actual +25%	566.4	30.7
Actual +40%	635.0	23.7
All daily rains of 0.1 to 1.0 inch, up by 10%	469.9	32.1
All daily rains of 0.1 to 1.0 inch, up by 25%	495.3	27.6
All daily rains of 0.1 to 1.0 inch, up by 40%	520.7	27.1
All daily rains >1.0 inch, up by 10%	480.1	29.6
All daily rains >1.0 inch, up by 40%	561.3	26.6
All daily rains ≤0.1 inch, up by 40%	459.7	34.4

The values of yields and rainfall levels are compared on table 3. The results are largely as expected. The results for soybeans in the covered plots show that 25% rain increases in typical wet and dry summers produced crop yield increases but with a minor decrease (-0.1 bu/acre) in average to average +25% for no apparent reason. The corn results are also partly anomalous. Past weather-crop research (Huff and Changnon, 1972) indicated that a wet summer made wetter by 25% would produce a crop yield decrease, and as shown in table 3, it did, by 7.4 bu/acre. The oddest result is the decrease in corn yields from a dry to dry +25% rain condition. Examination of the plot yield values provided a possible explanation for these two anomalous outcomes.

The unusual outcome in the covered plots include a decrease in bean yields from normal rainfall to normal +25%, were a result of 1 of 3 plots having an unusual yield value. In the "average year" for soybeans, the 3 plots yield values were 44.6, 44.7 and 54.8. The latter value was the single highest plot value and >4 bu/acre higher than any other plot, suggesting an incorrect or unrepresentative value. If the average rain value were the average of the two others, 44.7 bu/acre, the shift in bean yields in table 3 from normal rain to normal +25% would be +2.2 bu/acre, a reasonable figure.

Similarly, the corn yield decrease from dry rain to dry +25% (table 3) was odd. The dry summer +25% rain value for corn yields in table 2 appears too low and the 3 plot yield values were 97.9, 71.6, and 59.1 (the lowest of all plot values). If this low outlier considered erroneous were eliminated, the average for dry +25% would be 84.7 bu/acre. Then the shift in corn yields in table 3 from the dry rain level to the dry +25% level would be reasonable, +5.4 bu/acre, not a decrease of 3.1 bu/acre.

The values of the covered shelter plots are shown in Figure 3. The soybean and corn values both show: (1) highest yields in the mid-rainfall (near average) range of 300 to 400 mm; (2) slightly lesser yields with heavier summer amounts, >400 mm; and (3) the lowest yields with the lowest rain values. Given that these value are also dependent on the other weather conditions in 1987 (normal temperatures), the covered plots results indicate that the optimum rainfall for beans was about 300 mm (11.8") but was about 375 mm (~15") for corn. (Note that the average rain is 278 mm.)

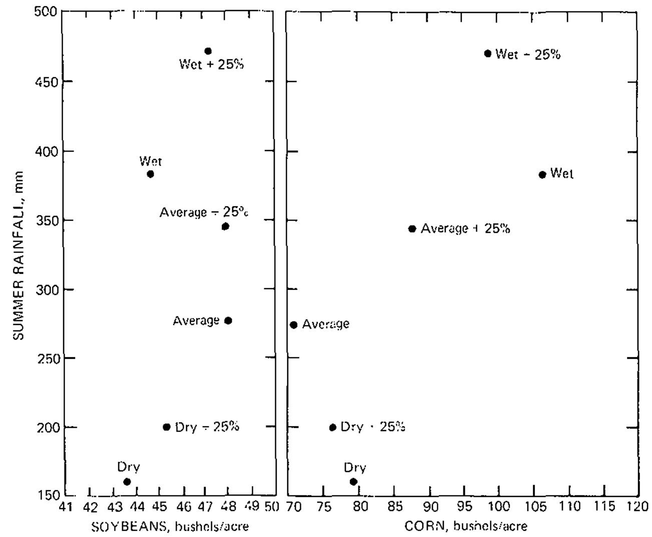


Figure 3. Summer rainfall and crop yields in covered plots, 1987

Table 3. Comparison of yield shifts between treatments in both plot areas.

Covered Plots	Shift in Soybeans (bu/acre)	% of base	Shift in Corn (bu/acre)	% of base
Dry Summer to Dry + 25%	+1.7	+3.9	-3.1	-3.9
Normal Summer to Normal +25%	-0.1	-0.2	+17.0	-24.0
Wet Summer to Wet +25%	+2.4	+5.3	-7.4	-7.0

Open Plots:	Shifts in soybean yields, bu/acre	% of base
Actual rain to +10%	-6.6	-20.2
Actual rain to +25%	-2.0	-6.1
Actual rain to +40%	-9.0	-27.5
Actual rain versus increases in raindays in 2.54 to 25.4 mm range		
Actual rain increased by 10%	-0.6	-1.8
Actual rain increased by 25%	-5.1	-15.6
Actual rain increased by 40%	-5.6	-17.1
Actual rain versus increases of all >25.4 mm rains		
Actual rain increased by 10%	-3.1	-9.5
Actual rain increased by 40%	-6.1	-27.8
Actual rain versus increases of all <.254 mm rains		
Actual rain increased by 40%	+1.7	+6.3

Corn yield outcomes were somewhat odd. The lowest yield came with the average rainfall; with slightly higher yields with dry summer rainfall levels (dry and dry +25%). Results may have been affected by the type of summer temperatures.

The results for the uncovered plots were limited to soybeans since wind damage to the corn plots (described above) affected the yields. The soybean-yield rain values for the 10 treatments selected are shown in table 2, and relevant yield comparisons are shown in table 3. The plot of summer rain against the soybean yields (Fig. 4) reveals that the actual summer rain experienced in 1987 was the best for beans and that all but one of the rain additions to simulate weather modification, decreased bean yields. Only the 40% increase to the days with <0.254 mm (0.1 inch), which included only 7 days in June-August, indicated a slight increase in yield. The results (Fig. 4) reveal that too much rain was damaging to bean yields. Apparently (given the 1987 temperatures and sunshine), the optimum rainfall for beans was in the 350 to 300 mm range, as revealed by the results of the covered plots (Fig. 3).

Further tests of the simulated increases in 1988 under different temperature and sunshine conditions should allow more definitive

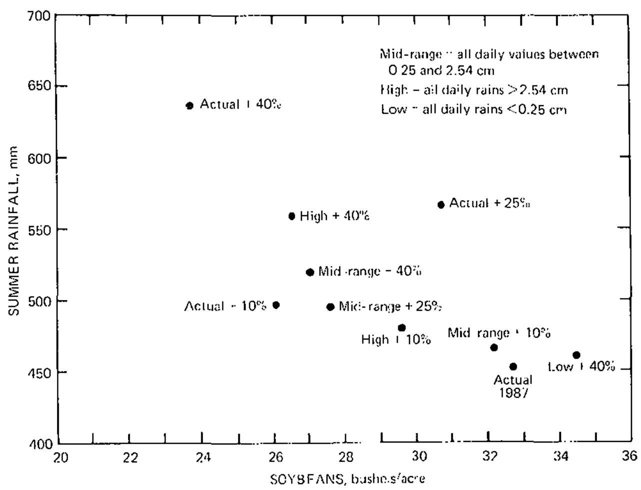


Figure 4. Summer rainfall and soybean yields in uncovered plots, 1987

interpretations of the rain-yield relations. The 1987 outcomes will also be compared with predictions from weather-yield regression models to help calibrate the models. The results for 1987 indicate, in general, that rainfall increases of 10 to 40% will increase yields of corn and soybeans if the actual rainfall is in the below to near average range. The increases will be relatively small, 4 to 20%, of that expected, or generally 3 to 6 bu/acre.

Acknowledgements. This research has been partly supported on two grants from NOAA: NA 86RAH06051 and NA 87RAH06051. The considerable assistance of Wayne Banwart and Eugene Ziegler of the University of Illinois, Agronomy Department, in managing the test plots is gratefully acknowledged.

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