Hailstorm Damage to Crops in Northeastern Colorado and an Analysis of Precipitation Anomalies Associated with a Cloud-Seeding Program in 1959

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Introduction

The High Plains area of eastern Colorado and Wyoming, and western Nebraska and Kansas, suffers from a dual problem of frequent shortages of precipitation and frequent hailstorms that inflict severe crop losses and property damage. Within this region, development of irrigation water supplies from surface and underground sources has permitted the development of irrigated agriculture. A large part of the region, however, does not have a suitable source of water for irrigation, and must depend on precipitation for crop production.

The severity of the hail problem is indicated by Figure 1, which shows that this region suffers from the highest average annual number of days with hail in the United States (9)[2].

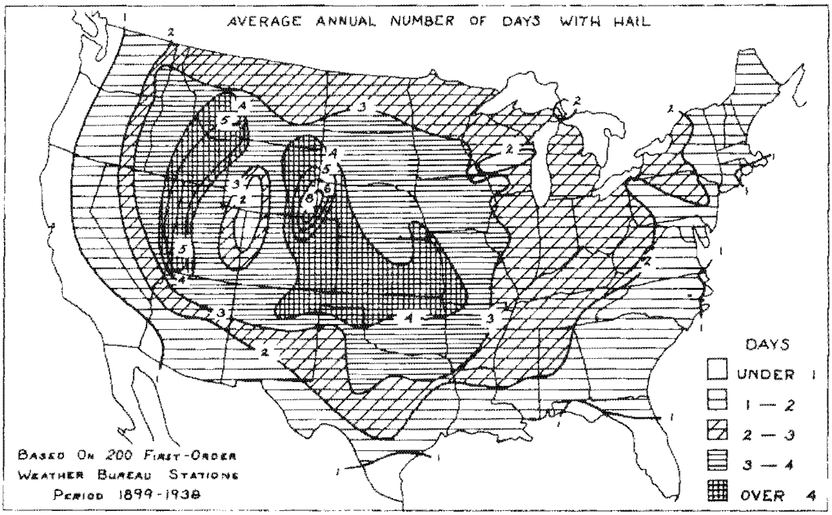

Figure 1.—Average annual number of days with hail for years 1899 to 1938. (Source: Climate and Man. Yearbook of Agriculture, U. S. Department of Agriculture, 1941, p. 730.)

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[2] Numbers in parentheses refer to literature cited.

The economic cost of hail damage is reflected in current hail insurance rates. The cost for crop-hail insurance under a standard "10 percent deductible" insurance policy in this region ranges upward to $22.00 per $100.00 insurance for a crop such as wheat (3). (The rate for sugar beets is one-half that for wheat, reflecting a greater resistance to hail damage by the beet plants.)

A cloud-seeding program was used in 1959 in northeastern Colorado in an attempt to reduce hail damage. In a "target" area of about 3400 square miles clouds were seeded with silver iodide generators by a commercial weather modification company, using five aircraft and about 125 ground generators.

A study was made to evaluate this operation. This paper, however, is limited to background information pertaining to methodology of evaluation of changes in hail damage, and to presentation of data on precipitation anomalies associated with the cloud-seeding program.

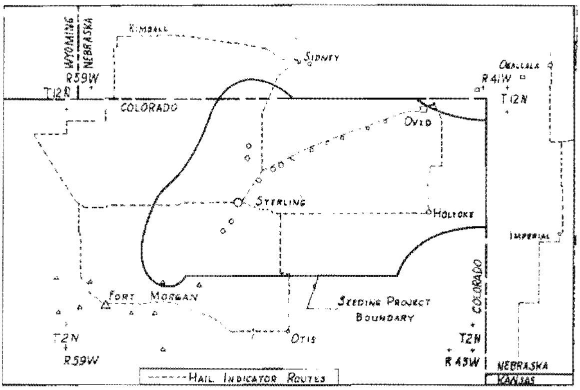

Figure 2.—Location of study area including The Great Western Sugar factory districts and associated beet dump areas. Δ is for the Fort Morgan factory district and associated beet dumps, ○ for Sterling, and □ for Ovid.

Procedure

Figure 2 shows the location of the target area and The Great Western Sugar Company Districts of Fort Morgan, Sterling and Ovid, Colorado. The data for the study were secured from observations in and bordering the target area.

During the study the following data were collected:

1. Information was obtained from a survey mailed to residents of the area living in or near Section 8 and 18 in each Township in Colorado between Township 3 to 12N and 42 to 59W inclusive. Cooperators were requested to report hail occurrences by mail, giving location, time of

hail occurrence, size distribution of hail, and concurrent weather phenomena including wind, lightning and precipitation amounts. A total of 389 reports of hail occurrences of this type were received between 15 May and 15 September 1959.

2. Data were obtained from periodic examination of approximately 250 hail indicating devices located in or near the target area. Figure 2 shows the routes along which the devices were located. A total of 358 indicators that had been damaged by hail were examined between 15 May and 15 September. Figure 3 is a schematic drawing of the hail indicating device.

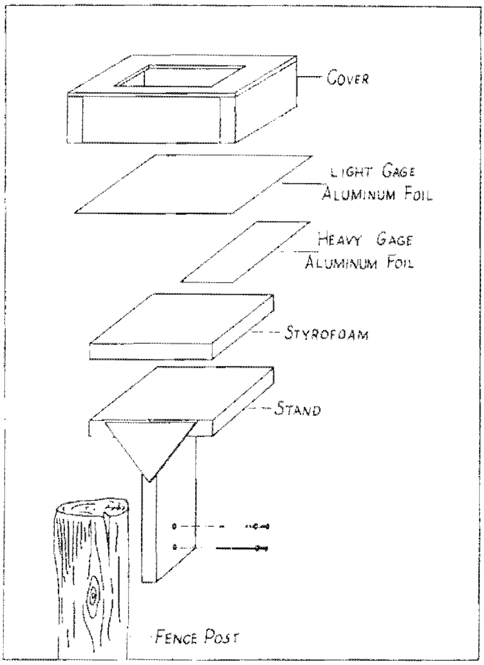

Figure 3.—Schematic diagram of hail indicating device.

3. Reports were obtained from the Weather Modification Company on locations and times of ground generator operation, and routes and times of seeding by aircraft.
4. Information on the amount and type of hail damage to sugar beets between 1929 and 1959 was obtained from the Ovid, Sterling, and Fort Morgan districts of The Great Western Sugar Company.
5. Reports of precipitation and other weather data were obtained from U. S. Weather Bureau cooperative observers in and near the area.

Results

A. Historical Records of Beet Damage

From the information in item 4 above the cumulative relative frequency of occurrence of light, medium, heavy, and total beet damage[3] was determined for The Great Western Sugar Company Districts of Ovid, Sterling and Fort Morgan[4]. The results are shown in Figure 4. Although the subjectivity of these measurements is recognized they are considered to be the best historical records of hail damage available.

Figure 4 shows that highest losses in 1959 were experienced in the Sterling factory district, with lowest losses in the Ovid factory district.

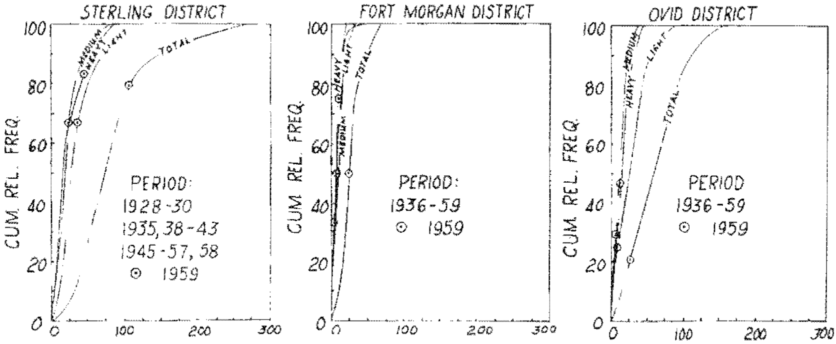

Figure 4.—Cumulative relative frequency in percent of hail damage to sugar beets in the Fort Morgan, Sterling, and Ovid, Colorado, The Great Western Sugar Company factory districts. Abscissa is the percent of acres planted that were damaged by hail during one season.

B. Hail-Precipitation Relations

Studies of hail in the Denver area by Beckwith (1) indicate that a relationship probably exists in the Denver area between the number of hail days and precipitation for the period from April to October. A rank correlation test (4) was performed to determine if a relationship might exist between percent of normal precipitation and percent of total acres of beets damaged.

The percent of normal precipitation for May-August for Sterling and Fort Morgan combined was correlated with the percentages of light, medium, heavy, and total damage to beets (in terms of percent of total acres planted[5]) for the Ovid,

[3] Great Western Sugar Company officials defined "light" damage as 25 percent or less leaf defoliation; "medium" as 25-50 percent defoliation; and 50 percent or more as "heavy" damage. Concerning the application of these standards one manager commented "of course, these gradations are subject to the individual subjective interpretations of each fieldman reporting the damage—and these variations are often as many as men who view the damage."

[4] The "Fort Morgan" district incorporates the former "Brush" district. Since the analysis was done on a percentage basis, a change of area does not affect the analysis.

[5] It should be noted that use of this definition permits hail damage in excess of 100 percent, since it is possible to experience damage at a point more than once during the season.

Sterling, and Fort Morgan factory districts of The Great Western Sugar Company. The results of this statistical test indicated that for all degrees of hail damage there was no significant relationship between percent of normal precipitation and percentage of beet acreage damaged. The results of this test are included in Table 1.

Table 1.—Results of rank correlation test between percentage of normal precipitation and percentage of beet acreage damaged by hail.

	N (Years)	r	$r_{.95}$
P vs. L	23	-0.035	0.352
P vs. M	23	0.278	0.352
P vs. H	23	-0.010	0.352
P vs. T	23	-0.059	0.352

where

P = percentage of normal precipitation (May to August) for Sterling and Fort Morgan combined.

L, M, H, T = percentages of beet acreages planted with light, medium, heavy, and total hail damage for Ovid, Sterling, and Fort Morgan factory districts of The Great Western Sugar Company.

r = rank correlation coefficient.

$$= 1 - \frac{6\,[\Sigma\,(Y_i - X_i)^2]}{N\,(N^2 - 1)}$$

Figure 5 is a scatter diagram of hail damage to beets in percent of acres planted and precipitation in percent of normal for the areas described. The line does not indicate any correlation but is merely drawn such that one-half the data are above the line. The years that fell above the line were then examined to find if they had a preponderance of hail days resulting from frontal or non-frontal meteorological conditions (5). From this analysis it was concluded that a preponderance of frontal or non-frontal hail days is not an important factor in determining the extent of hail damage. It may be noted that nine of the past thirteen years are positioned above the line on Figure 5. This indicates a possible inconsistency in the data. A possible explanation is that the system used to report beet damage may have been improved in the past few years.

C. Hail Intensity Measurements by an Energy Parameter

Early in the study, it was decided that a better statistic than number of days with hail was needed to determine any effects that cloud seeding might have on hail intensity and occurrence. Using indicators as shown in Figure 3, it was found that a satis-

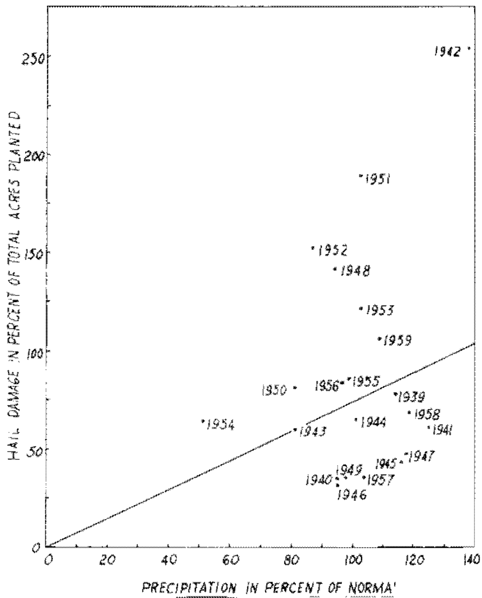

Figure 5.—Scatter diagram of total hail damage to sugar beets (Fort Morgan, Sterling and Ovid factory districts) vs. percent of normal precipitation (May-August) at Fort Morgan and Sterling.

factory approximation of the energy per square foot delivered by a hailstorm could be determined from the number and size of the dents left on the aluminum foils (6). This estimate of the impact energy from the hailstorm, in units of foot-pounds per square foot, is hereinafter called an "energy number."

During field use of these indicators, it was observed that medium crop damage was usually present when the energy number was between 50 and 100 ft-lbs per square foot. This is only approximate because crop damage is dependent not only on the intensity of the hail, but also on the stage of growth of the crop. For example, sugar beets are quite sensitive to hail damage during the seedling stage and become more resistant to hail damage as they mature. Wheat has different characteristics, being extremely sensitive to hail damage at maturity.

From reports of hailstone size, number, and attendant wind furnished by the cooperative observers, an approximation was made of the energy number of the hail that fell at the point of observation[6]. A rank correlation test (4) was made between this energy number[6] and the amount of precipitation concurrent

[6] This estimate was based on the laboratory calibration of the hail indicators, as described in reference (6).

with the hail. It should be noted that this test differs significantly from the one described previously. In the former test the variables, hail and precipitation, were compared by the use of average values covering large areas, while the second test compares these variables at a large number of discrete points. The results of this test indicate that there is a high probability of a positive relationship existing between the energy number of a hail occurrence and the precipitation delivered by the storm. This relationship appears to be present in both seeded and unseeded hailstorms. The results of the test are included in Table 2.

Table 2.—Results of rank correlation test between estimated energy per square foot from hail occurrences[1] and the attendant precipitation.

Month	Seeded cases		Non-seeded cases	
	N	r	N	r
May	85	0.183*	93	0.205*
June	34	0.129	63	0.219*
July	47	0.383**	38	0.127*
Aug.	5	.90*		....

* = significant at the 95 percent level

** = significant at the 99 percent level

r = rank correlation coefficient

$$r = 1 - \frac{6\,[\Sigma\,(Y_i - X_i)^2]}{N\,(N^2 - 1)}$$

N = Numbers of pairs of observations

[1] Energy values were estimated from reports of number and sizes of stones and attendant wind reported by voluntary observers.

The energy number is a function of the number and size of stones and their fall velocities. If it is hypothesized that greater numbers of ice nuclei are available following cloud seeding, it should follow that the available water in the cloud would be distributed in a larger number of drops and that the diameter of hailstones would be reduced. If one hypothesizes that cloud seeding could thus reduce the diameters of the stones from d to d′ without changing the total quantity of precipitation that falls as hail, then the energy number of a hail occurrence would be reduced. Figure 6 shows the effect of various assumed changes in hailstone diameter on the hail impact energy change ratio,

$\frac{E'}{EK}$, where

E' = energy number resulting from hail after the hypothesized change in diameter of the stones from d to d'.

E = the energy number resulting from hail before the hypothesized change in diameter of the stones from d to d'.

K = a factor associated with the cloud seeding. If cloud seeding produces no change in the total amount of water appearing as hail, K would be equal to unity. (The value of K is not known.)

Figure 6 shows, for example, that if seeding reduced the hail diameter 10 percent (d'/d = 0.9) and at the same time increased the total amount of hail 10 percent (K = 1.1), the energy number that would result from the hail following the hypothesized changes would be essentially unchanged. The calculations for producing Figure 6 are explained in Table 3.

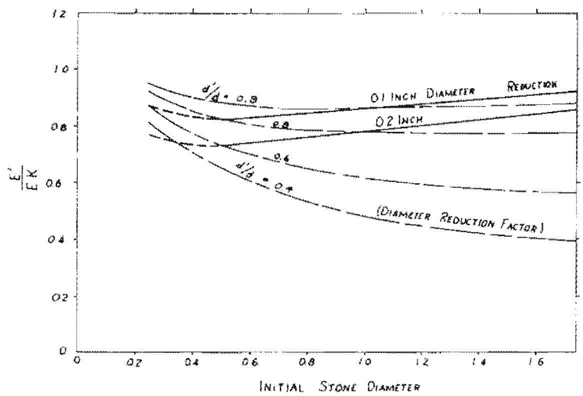

Figure 6.—The effect of hypothesized changes in diameter of hailstones on hail impact energy change ratio, (E'/EK). The 0.1 and 0.2 inch diameter reduction assumes that each stone is reduced by 0.1 or 0.2 inch from the initial diameter. The diameter reduction factors are the ratios of the assumed final diameter d' to the initial diameter d.

The following analysis considers the effects of various hypothesized changes in hail intensity on damage to crops having differing susceptibility to hail damage. The basic data in the analysis are the observed frequencies of occurrence of energy numbers in northeastern Colorado, during the summer of 1959 for hail events not affected by cloud seeding. The energy numbers were obtained from measurements of number and sizes of dents from hail indictors (Figure 3).

Consider the area under the curve of the observed frequency distribution of energy numbers (not shown). For such a curve, the ordinate is in units of events per season, and the abscissa in units of energy per event, which can be considered the same as damage per event if the assumption is made that a crop suffers damage if the given energy number is exceeded. Each observed energy number in excess of the value for the threshold of crop damage then represents a unit of hail damage for that hail event.

Table 3.—Computations for Figure 6.

A plot of hailstone-terminal velociety in still air was prepared using the fluid mechanics formulas[1].

$$d = \left(\frac{3\ R^2 \mu^2 C_d}{2\rho'\ g\rho} \right)^{1/3} \quad \text{and } R = \frac{\rho V d}{\mu}$$

where

R = Reynolds number
d = Diameter of hailstone
μ = Viscosity of air
C_d = Coefficient of drag
ρ' = Density of hail
g = Gravitational constant
ρ = Density of air

The total velocity, W, of the stone when it hits the ground was assumed tto be the vector sum of the terminal velocity in still air, V, plus the concurrent surface wind velocity.

The kinetic energy, T, of a single stone, was then computed as

$$T = 1/2\ mW^2$$

where

m = mass of stone
W = Velocity of stone

For one inch depth of precipitation and a given stone size the number of stones per square foot was computed. The number of stones multiplied by the kinetic energy per stone yields the energy number for the assumed depth of precipitation and a particular stone diameter. The impact energy change ratio was computed as the ratio:

$$\frac{E'}{EK} = \frac{\text{impact energy for stones of diameter } d' \text{ from one in. depth of water}}{\text{impact energy for stones of diameter } d \text{ from one in. depth of water}}$$

Figure 6 was computed for the case of zero surface wind. Results would be comparable for non-zero surface winds.

[1] Foster, D. S., and Bates, F. C. 1956. A Hail Size Forecasting Technique. Bull. of the Am. Meteor, Soc. 37(4): 125-141.

The area under the curve to the right of a particular energy number then represents

$$\frac{\text{damage}}{\text{event}} \times \frac{\text{events}}{\text{season}} = \frac{\text{damage}}{\text{season}}$$

The ratio of the area under the curve to the right of a particular energy number to the total area under the curve is defined as "Relative Damage." The particular energy number for which crop damage is assumed to begin is defined as the "Critical Energy Number," (E_c).

Figure 7 shows the relation between Relative Damage and Critical Energy Number. The line labeled $\Delta E = 0$ is based on the observed frequency distribution of energy numbers for 1959 for hail events affected by cloud seeding, and shows that a change in E_c from zero to 10 ft-lbs per ft^2 would reduce the Relative damage by about 50 percent.

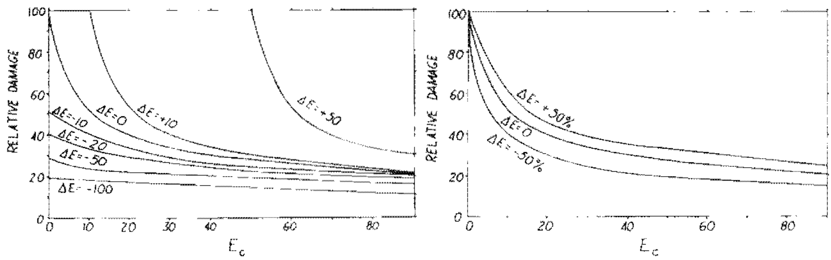

Figure 7.—Relative crop damage as a function of critical energy number (E_c) for various hypothesized changes in energy number associated with cloud seeding. Relative damage for the 1959 season (non-seeded cases) is given by $\Delta E = O$. Hypothesized changes are (a) changing the energy number for each hail event by a fixed amount and (b) changing the energy number for each hail event by a fixed percentage.

Let us hypothesize that cloud seeding might change the observed frequency distribution of energy numbers. Two types of changes are hypothesized. For the first, a change in each energy number of a fixed amount is hypothesized. ($\Delta E = -10$, -20, -50, -100, $+10$, $+50$, ft lb/ft^2 in Figure 7a.) For the second, a percentage change in each energy number is hypothesized. ($\Delta E = \pm 50$ percent in Figure 7b.) The effects of such changes on the relations between Relative Damage and Critical Energy Number are shown in Figure 7. Figure 7a shows decided changes in relative damage for sensitive crops for a given hypothesized change in energy numbers, while for more hardy crops the change in Relative Damage is smaller for the same hypothesized changes in energy numbers. For hypothesized changes of a fixed percentage, the effect on Relative Damage is greater at higher critical energy values (Figure 7b).

The foregoing analysis was based on the assumption that crop damage and energy number are directly related. While physically reasonable, there has not been an opportunity to study this problem in detail. Figure 8, developed from laboratory calibration of the hail indicators, shows the possible combinations of parameters that will produce a given energy number. The parameters are: the number of stones per square inch; the diameter of the stone in inches; and the surface wind velocity in miles per hour. From Figure 8 it may be seen that there is a wide variety of these parameters that can produce a particular energy number.

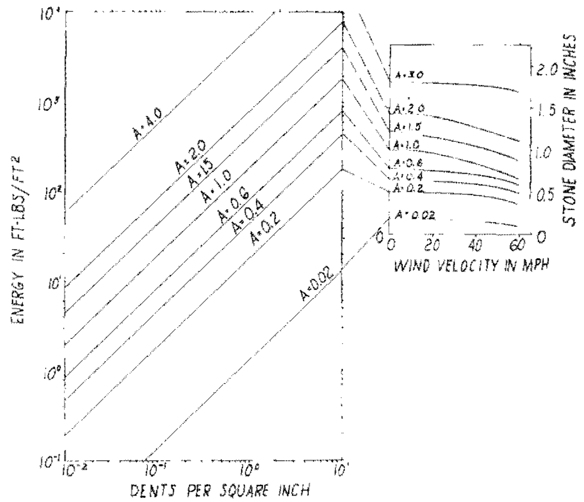

Figure 8.—Combinations of parameters that can produce a given energy number.

D. Precipitation Anomalies

The total precipitation in and near the target area for the months of May-August 1959, is shown in Figure 9. The percentage of normal precipitation for the same area for the same period is shown in Figure 10. Both figures were derived from data obtained from official U. S. Weather Bureau cooperative observers.

A "target-control" analysis was performed to attempt to detect differences in amounts of precipitation received in the target area as compared with adjacent control areas. The procedure used to obtain the transformed normalized precipitation variables τ_x (control) and τ_y (target) was identical with that described by Thom (8), except that all storms in the historical record were used in the analysis. The transformed normalized values for the target were plotted vs. concurrent values for the control and fitted with a least-squares line. Confidence bands of ± 1, 2, and 3 standard errors were computed (7:p137).

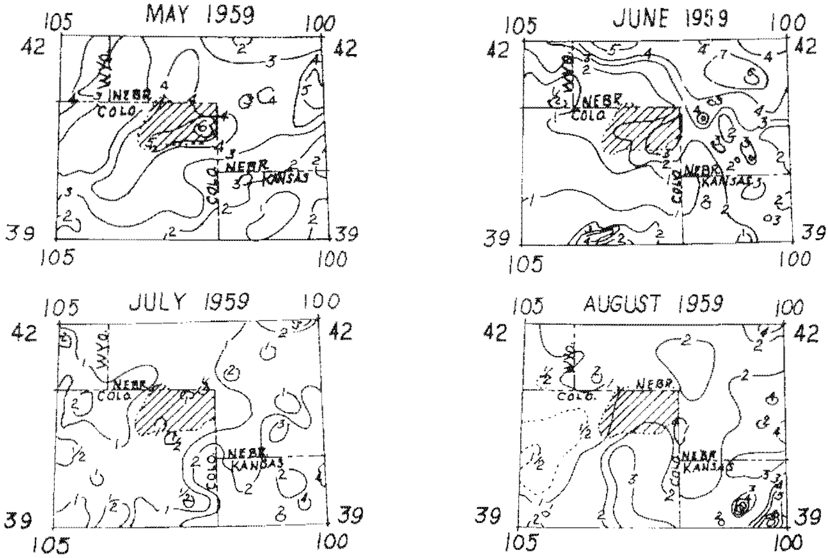

Figure 9.—Total observed precipitation in and near the study area during the months of May-August, 1959.

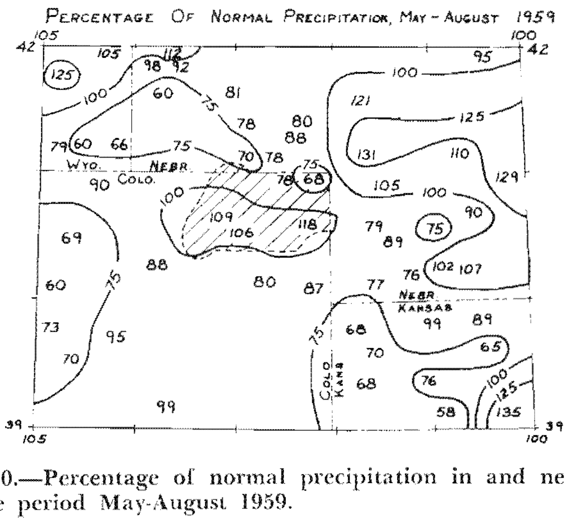

Figure 10.—Percentage of normal precipitation in and near the study area for the period May-August 1959.

Table 4.—Source of data used in target-control analysis.

Month	Target	Control	Years of record	Number of storms	Correlation coefficient
May	Sterling, Ovid, Leroy, Holyoke, Fleming	Greeley, Fort Collins, Fort Lupton	1942-48, 1950	26	0.77
June	Sterling, Ovid, Leroy, Holyoke, Fleming	Akron, Yuma, Wray	1942-44, 1944-50	40	0.90
July	Sterling, Ovid, Leroy, Holyoke, Fleming	Pine Bluffs, Kimball	1944-50	45	0.66
August	Sterling, Ovid, Leroy, Holyoke, Fleming	Akron, Yuma, Wray	1942-46, 1948-49	36	0.65

Eleven storms produced precipitation on the target and control stations between 15 May and 15 September 1959. The values of storm rainfall for these eleven storms were then superimposed on the diagrams. The results are shown in Figure 11, and summarized in Table 5.

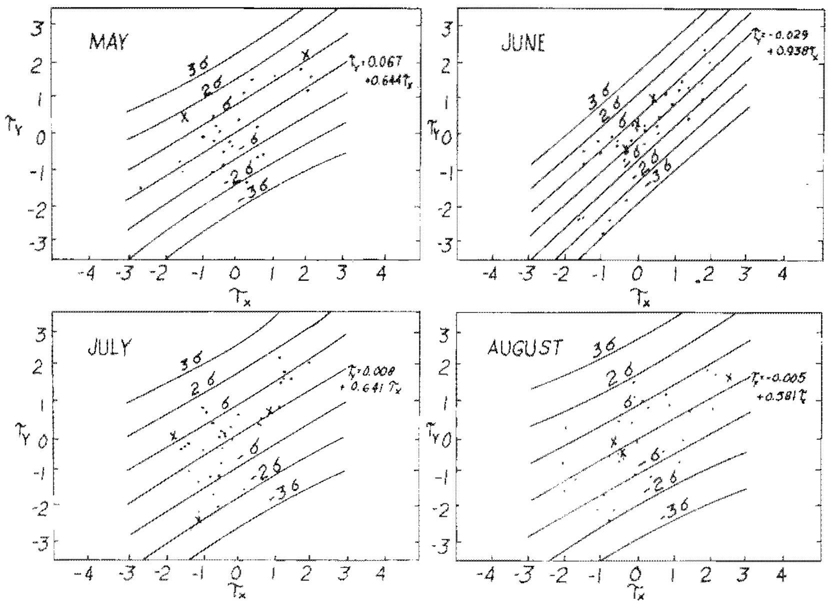

Figure 11.—Target-control analyses for precipitation anomalies. Values shown are the normalized transformed precipitation totals for control (r_x) and target (r_y) stations. Values for 1959 are marked "X."

Table 5.—Numbers of cases of storm precipitation in 1959 that fall within given standard errors of estimate from regression.

	−3σ		−2σ		−1σ		0		+1σ		+2σ		+3σ
May										2			
June								1		1			
July				1				1		1			
August						1		2					
Total[7]				1		1		4		4			

Although no single storm event departs by more than two standard errors from the regression, it is of interest to note that 8 out of 10 cases indicate a positive precipitation anomaly. In the absence of outside influences on the distribution of precipitation on the target and control stations, the chances of positive and negative anomalies would be equally likely. The probability of getting 8 or more positive anomalies out of ten cases by chance from an unbiased population is 0.0547.

Summary

A study was made of methodology of evaluating changes in hail damage and the effects of a cloud-seeding program on precipitation in northeastern Colorado, in 1959. Records of hail damage to beets from The Great Western Sugar Company factory districts were used as historical data to compare with the loss experience in 1959.

Statistical tests failed to reveal a significant degree of correlation between seasonal precipitation over the study area and hail damage to beets.

An energy parameter (units: ft lbs per ft^2) was used to describe hail impact energy resulting from a hailstorm. A significant positive correlation was found between this parameter and concurrent precipitation at a large number of discrete points.

If it is hypothesized that cloud seeding produces a larger number of smaller hailstones without changing the total quantity of precipitation which falls in the form of hail, then the hail

[7] One value for 1959 fell on the regression line.

impact energy from a given hailstorm will be decreased. This decrease, however, might be offset if seeding were to produce a greater quantity of precipitation falling in the form of hail.

If it is hypothesized that cloud seeding can reduce the hail impact energy of each hail event by a given amount, then the greatest benefits from such seeding would accrue to highly sensitive crops. If it is hypothesized that cloud seeding can produce a percentage reduction in hail impact energy of each hail event, the greatest benefits accrue to the more sturdy crops.

The assumption that hail damage is proportional to hail impact energy needs verification from further studies, since a given value of hail impact energy can result from a wide range of parameters including numbers and sizes of stones, and attendant wind.

Precipitation in the southern half of the target area for the period May-August 1959 was higher than normal and higher than adjacent areas, except to the northeast.

A target-control analysis for the season indicates that 8 out of 10 storms showed positive precipitation anomalies associated with the cloud-seeding operation. While results from individual storms are not significant, the probability of getting these observed numbers of positive anomalies for individual storms by chance from an unbiased population is 0.0547.

Acknowledgments

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