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VARIATIONS IN RAINFALL AND INSURED CROP-HAIL LOSSES ASSOCIATED WITH OPERATIONAL CLOUD SEEDING IN SOUTH DAKOTA

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Abstract. A brief review of operational cloud seeding programs in South Dakota is given, followed by an evaluation on the basis of rainfall data and insured crop-hail loss data for the years 1948-1978.

All of the projects used silver iodide as the seeding agent, but a wide variety of generator types, seeding rates, and delivery methods was used.

In years with aircraft seeding over small areas, both rainfall and hail damage tended to be larger in target than in non-target counties. The data available do not show such a trend for years when ground-based generators were employed.

In years when 40% or more of the state was seeded, the results for target and non-target counties became indistinguishable in terms of both rainfall and crop hail damage. However, increases in the area included in cloud seeding programs, using either ground based or airborne generators, were associated with an apparent net hail suppression effect, extending over the entire state. The rainfall data do not display such a trend.

1. INTRODUCTION AND HISTORICAL BACKGROUND

This paper summarizes the results of a 3-year investigation into the statistics of summer rainfall and crop-hail losses in South Dakota before, during, and after extensive operational cloud seeding programs in that state. Portions of the work have been reported previously at two scientific meetings (Brown et al., 1979; Dennis et al., 1980).

The investigation has been motivated in part by repeated inquiries from government agencies and private parties about the effects of operational cloud seeding programs in South Dakota. In addition, the data related to the operational seeding appeared to be a potential source of information about seeding effects and the relative merits of different seeding methods.

Cloud seeding in South Dakota has been intended generally to increase agricultural production by moderating certain aspects of the state's harsh continental climate. Crop yields are nearly always limited by available moisture, and are sometimes reduced by hailstorms. The average annual rainfall ranges from over 600 mm (24 in) in the southeast corner of the state to about 300 mm (12 in) in the northwest corner. The Black Hills at the extreme west end of the state have an average annual rainfall of up to 750 mm (30 in) and are forested. Hailstorms are frequent and crop damage (in 1980 prices) averages over $50,000,000 per year.

There have been a few winter projects in South Dakota, but nearly all of the operational projects have involved attempts to increase rainfall, suppress hail, or both, during the growing season by seeding cumulus and cumulonimbus clouds with silver iodide (AgI). Information on each project is given in Schock's (1977) summary of weather modification activities in Minnesota, North Dakota, and South Dakota. Project reports, newspaper clippings, and correspondence about the projects are available in the Bruce Collection, which was donated to the Devereaux Library, South Dakota School of Mines and Technology, by the family of the late M. N. Bruce, first chairman of the South Dakota Weather Control Commission.

All of the operational seeding in the 1950's was by ground based AgI generators. Most of the projects were conducted by the Water Resources Development Corporation (WRDC) using generators burning coke pellets impregnated with AgI (e.g., Krick, 1952). Each generator consumed only a few grams of AgI per hour. The WRDC generators were widely scattered. For example, newspaper accounts indicate that one project covering several counties in the west central part of the state was served by a network of about 25 generators located throughout western South Dakota and adjacent parts of North Dakota, Montana, Wyoming, and Nebraska. A competing firm used acetone generators charged with AgI•NaI solutions on one project in northwestern South Dakota in 1952 and 1953 (e.g., Battle et al., 1952). From personal knowledge gained subsequently as an employee of that company, the senior author estimates AgI consumption on that project at 10-20 g per generator hour.

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Nearly all of the operational projects after 1960 used aircraft seeding. The first seeding aircraft were equipped with acetone generators. AgI•NaI solution was used in many, if not all, of the early projects. Some of the operators switched to $AgI \cdot NH_4I$ solution about 1970 in the hope of obtaining higher ice nucleating efficiency at temperatures just below 0°C. Consumption rates varied from perhaps 100 to 400 g per generator hour. Many aircraft were equipped with two wing-tip mounted generators, and it became a common practice to operate both simultaneously for hail suppression.

Some of the earliest aircraft seeding missions involved cloud penetrations around the -5C to -10C levels. There seems to have been an impression among the seeding pilots that in-cloud seeding was more effective than seeding below cloud base. However, safety considerations caused most seeding of intense convective storms, especially seeding for hail suppression, to be conducted from below cloud base.

A state-supported program was operated from 1972 through 1975. The seeding was conducted entirely from aircraft. The seeding pilots were guided by radioed instructions from radar equipped field offices. The aircraft carried generators charged with $AgI \cdot NH_4I$ solution; AgI consumption rate varied from 150 to 300 g per generator hour (e.g., Williams, 1973). Pyrotechnic devices capable of consuming 200 g or more of AgI per minute were also provided for hail suppression attempts. A detailed strategy evolved to guide the seeding operations (e.g., Williams, 1974). Hail suppression was the primary objective whenever a hail threat was considered to exist. At other times, promising cloud formations were seeded to increase rainfall. Seeding was generally done from below cloud base, but cumulus congestus and stratiform clouds were sometimes seeded near the -5C level to initiate precipitation.

Individual counties had the option of participating or not participating in the state-supported program on a cost-share basis. Figure 1 shows the participating counties in 1972, the first year, and in 1974, the year of maximum participation. The state program was not renewed for 1976, but two projects were operated by groups of counties with some state support. Mewes (1977) has described the history of cloud seeding in South Dakota from a sociological point of view, with particular reference to the organized opposition which caused the state legislature to withdraw financial support from the state program in 1976.

Seeding in 1977 and 1978 was conducted only in Harding County, which is in the northwestern corner of the state. It was conducted by aircraft operating with guidance from radar meteorologists at the Bowman field office of the North Dakota Cloud Modification Project.

In addition to the operational projects, South Dakota has been the site of several experimental cloud seeding projects. Most of the experimental seeding occurred in the western part of the state from 1964 through 1972 as part of the U.S. Department of the Interior's Project Skywater. It involved a variety of seeding agents, but AgI was by far the most commonly used (Dennis et al., 1974). The only experimental seeding after 1972 was the seeding of a few heavy cumulus over the Black Hills with an organic agent, 1,5 dihydroxynaphthalene, in the summer of 1974 (Fukuta et al., 1975).

2. PREVIOUS EVALUATION ATTEMPTS

There have been a number of attempts at evaluation of operational cloud seeding projects in South Dakota.

In the 1950's, the Water Resources Development Corporation distributed reports showing rainfall accumulations during ground-generator operational periods as percentages of monthly normals. They also made some use of control areas and historical analogues of seeded storms in an attempt to sharpen the evaluation of WRDC projects (Krick, 1952). Todd used the historical target-control regression method to evaluate a 1952 project using ground-based acetone generators in the northwestern part of the state (Battle et al., 1952). The Final Report of the Advisory Committee on Weather Control contains "An Evaluation of Commercial Cloud

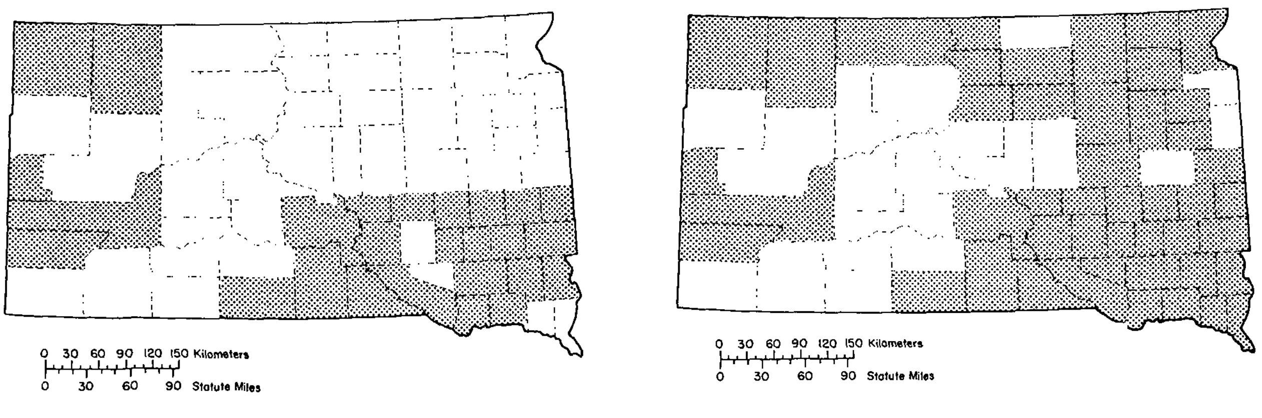

Fig. 1: South Dakota counties participating in state supported cloud seeding program, shaded; (a) 1972; (b) 1974.

Seeding Operations Conducted During the Summer Months in South Dakota," (Berndt, 1957). However, it presents proposed methods for determining changes in rainfall and possible associated economic benefits, rather than an actual evaluation, because Berndt believed that the data available to him were too scanty to sustain any conclusion about seeding effects.

Bruce performed some unpublished evaluations, mostly involving target-control comparisons, of early seeding projects.[2] Boyd (1972) examined a sample of seven aircraft seeding projects. Two of them were designed to suppress hail as well as stimulate rainfall; the other five were for rain increase only. Boyd found tentative indications of substantial rainfall increases, but no evidence of effects upon hailfall in the two hail suppression projects.

Brown et al. (1969) examined rainfall downwind of several projects in both North Dakota and South Dakota in a search for large-scale seeding effects. They found inconclusive evidence that rainfall per storm increased with the advent of seeding programs.

Staff members of the state Division of Weather Modification made some use of target-control evaluations. In one study, Donnan (1973) evaluated the effects of individual seeding flights with floating targets immediately downwind and controls immediately upwind of seeding tracks. The present authors consider that method subject to bias, because cloud systems were selected for seeding only if they looked promising and, in any event, were generally moving eastward toward regions with larger natural rainfall.

Miller et al. (1976) and Pellett et al. (1977) compared the insured hail loss data and the rainfall data, respectively, for the target and non-target counties for the period 1972-1975. Both groups of authors considered the years prior to 1972 as essentially unseeded years. They used data from those years in permutation tests to establish p-values for differences between target and non-target counties for the years 1972-75. Recognition of the need to overcome this shortcoming of the analysis by Miller et al. (1976) was one of the reasons for undertaking the present study.

3. DATA BASE FOR PRESENT STUDY

3.1 General Remarks

The evaluation required data pertaining to the seeding, to the rainfall, and to crop-hail damage, which were obtained from, respectively, the report by Schock (1977), the National Climate Center (NCC), and the Crop-Hail Insurance Actuarial Association (CHIAA). The hail reports are therefore weighted by those townships within each county that had the most insured crops; a few townships in the western end of the state never had any insured crops at all during the period under investigation. Although factors other than hail intensity affect hail insurance payouts, the usual climatological data are completely inadequate to characterize hail occurrences on an annual basis.

As most of the operational projects ran during the spring and summer, the analysis was limited to data for the months of May through August only (hereinafter called the growing season). For reasons to be discussed below, the study was further limited to data from the 31-year period of 1948 to 1978, inclusive. Because most of the seeding projects were organized by counties, the data for the evaluation were organized in the same way.

3.2 Seeding

The fraction of the area of South Dakota covered by both operational and experimental cloud seeding each year during the growing seasons of 1948 through 1978 is shown in Table 1, which is from Dennis et al. (1980).

The fractional coverage was estimated taking into account, with appropriate weighting, such factors as the inclusion of a county in a project for only a part of a season. The pecularities of each experimental project, for instance, the limitation of seeding to daylight hours only, or to days selected in accordance with a randomization scheme were also considered.

The operational projects were classified initially according to stated objective (rain increase or hail suppression), number of AgI generators per unit area, availability of weather radar, and so on. Preliminary analyses of the resulting data sets led nowhere. The only classification retained was the distinction between ground-based and aircraft operations (Table 1). The "Type of Seeding" listed in Table 1 applies to operational seeding only, even though the "Fraction of State Seeded" reflects all types of seeding. Only one year (1968) had operational projects of both types. It is represented in Table 1 and in some figures below by two entries (Dennis et al., 1980).

3.3 Rainfall and Hailfall Data

As noted above, rainfall and hail damage data were obtained from NCC and CHIAA, respectively. The analysis was limited to years from 1948 onward to avoid the extreme drought years of the 1930's, and because of apparent improvements in the compilation of hail statistics just after World War II.

The county-year was adopted as the basic unit for study. As South Dakota has 67 counties and the period under study was 31 years, the decision implied that there would be 2077 sample values for each variable chosen for study. However, counties that were only partly seeded or were seeded experimentally in a given year were dropped from the analysis, which reduced the basic data set to 1990 values for each variable studied. Some other data were missing due to a county not having a rain gage operating in a given year or due to a lack of CHIAA insurance records.

The basic rainfall statistic for each county year is the average growing season rainfall, which is the arithmetic average of the rainfall recorded at the climatic stations in the county during May through August.

The basic hail damage statistic chosen for analysis was the loss-cost ratio, which is the

[2]Available in the Bruce Collection, Devereaux Library, South Dakota School of Mines and Technology.

TABLE 1: Type of seeding, fraction of state seeded, and mean ranks for non-target and target counties by years

Year	Type of Seeding*	Fraction of State Seeded (%)	Mean Rainfall Rank Non-target	Mean Rainfall Rank Target	Mean Loss-Cost Rank Non-target	Mean Loss-Cost Rank Target
1948		0	24.1		15.3	
1949		0	8.9		12.3	
1950		0	8.5		14.3	
1951	G	38	24.1	21.4	12.0	12.2
1952	G	36	12.5	16.0	12.8	12.8
1953	G	33	21.9	23.6	14.6	12.4
1954	G	26	16.8	18.5	11.8	7.4
1955		0	14.6		18.3	
1956	G	6	20.1	14.2	24.8	24.0
1957	G	6	20.9	18.9	17.4	18.7
1958		0	12.4		14.6	
1959	G	8	7.7	4.4	17.2	22.5
1960		0	17.8		17.2	
1961		0	11.4		17.3	
1962	A	11	26.1	27.9	18.2	19.3
1963	A	8	23.1	28.2	18.6	23.6
1964	A	8	18.1	19.0	16.8	20.9
1965	A	8	13.9	22.8	16.3	19.4
1966	A	12	20.8	26.0	15.3	18.0
1967	A	18	18.7	19.0	16.9	21.7
1968	G	20	21.5	13.2	19.6	16.0
1968	A	20	21.5	25.0	19.6	24.8
1969	A	9	17.5	14.1	21.4	22.3
1970	A	11	7.3	4.7	19.7	11.6
1971	A	14	12.9	9.5	13.4	18.5
1972	A	35	14.8	17.9	17.4	11.6
1973	A	56	4.5	4.7	11.6	11.3
1974	A	63	9.6	8.2	11.9	13.7
1975	A	58	17.7	17.9	12.2	11.0
1976	A	21	8.3	10.9	13.6	15.0
1977	A	4	17.2	18.5	18.3	31.0
1978	A	4	18.9	25.5	16.0	18.0

*G = ground   A = aircraft

arithmetic average of the rainfall recorded at the climatic stations in the county during May through August.

The basic hail damage statistic chosen for analysis was the loss-cost ratio, which is the ratio of losses paid out throughout the county each year to the total insured liability. We compared it to other possible response variables, such as the fraction of the townships in a county reporting hail damage, and found them to be closely correlated. The need for a response variable other than the actual hail damage claims paid is obvious from Fig. 2, which shows the total insured liability as well as the loss-cost ratio calculated for the state as a whole. The loss-cost ratio suppresses variations due to changes in cropping patterns, prices, and insurance-buying practices, although some uncontrolled variations due to these factors may well remain.

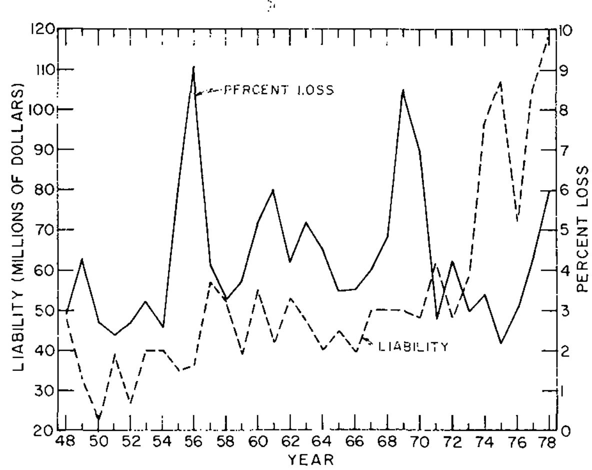

Fig. 2: Insurance liability (dashed line) and loss-cost ratio in percent (solid line) for the State of South Dakota, 1948-1978, inclusive.

3.4 Use of Ranks

The western part of South Dakota is drier and more prone to hail than is the eastern part. Miller et al. (1976) had to divide the state into five regions to obtain statistical homogeneity of hail loss-cost ratios.

One part of the analysis given below compares events in target and non-target counties. The climatologcial variations could lead to erroneous indications of seeding effects due simply to a concentration of target counties at one end of the state or the other. For that reason, the actual rainfall and loss-cost ratio for each county year have been replaced by ranks, which are a measure of how wet (or how hail-prone) the year in question was in that county compared to the other 30 years in the data sample. The ranks thus obtained are referred to below as rainfall and hail loss ranks, respectively. Increasing ranks are indicative of increasing average rainfall and of increasing loss-cost ratio.

4. EXAMINATION OF STATEWIDE TRENDS

The designs of the operational programs did not specify any evaluation methods. Therefore one is free to choose any reasonable approach. Each statistical approach implies the acceptance, perhaps unconsciously, of a corresponding model of how seeding changes precipitation, and is a test of whether or not that model was applicable to the particular situation under investigation. Failure to detect a seeding effect according to one model does not prove that no effect exists, so curiosity leads one to analyze the data again and again, assuming a different model each time. In doing so, one must remain alert to the hazards associated with multiplicity in statistical approaches to a data set.

A very simple approach is to consider the response of the state as a whole to the presence of cloud seeding projects. Figure 3 shows the mean of the rainfall ranks and the mean of the hail loss ranks for the individual counties for each year from 1948 through 1978. The mean rainfall rank and mean hail loss rank are independent of each other for this data sample. The correlation coefficient for the two variables is 0.3, which is not significantly different from zero at the 95% confidence level. Hail losses were low during the early 1950's and the middle 1970's, two periods with extensive operational projects. The question immediately arises whether the low hail losses were due to seeding or to natural climatological variations.

The mean rainfall rank and mean hail loss rank for each year are plotted against the fractional coverage by cloud seeding projects in Fig. 4 and Fig. 5, respectively. There is no significant correlation between mean rainfall rank and fractional coverage by seeding projects. The significant negative correlation (r = -0.72) between mean hail loss rank and fractional seeding coverage leads us to draw a regression line as shown on Fig. 5. While the regression line of Fig. 5 shows the mean hail loss rank decreasing as cloud seeding projects become more widespread, the points at the left show that the mean hail loss rank was higher for years when a small part of the state was seeded than when

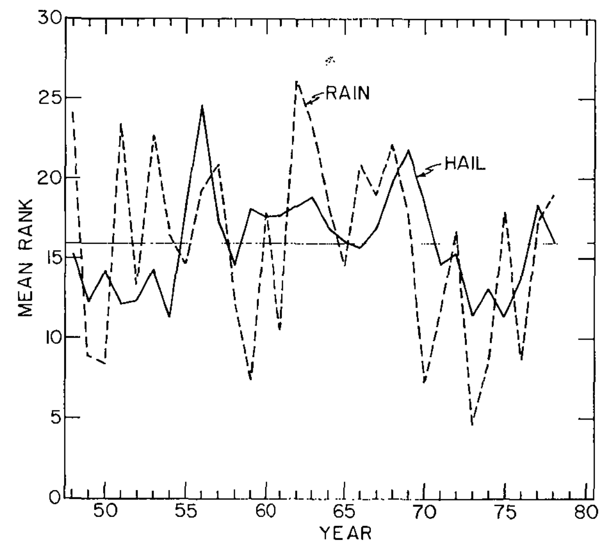

Fig. 3: Mean rainfall rank and mean hail loss rank, 1948-1978, inclusive. A rank of 16 is the expected value in both cases.

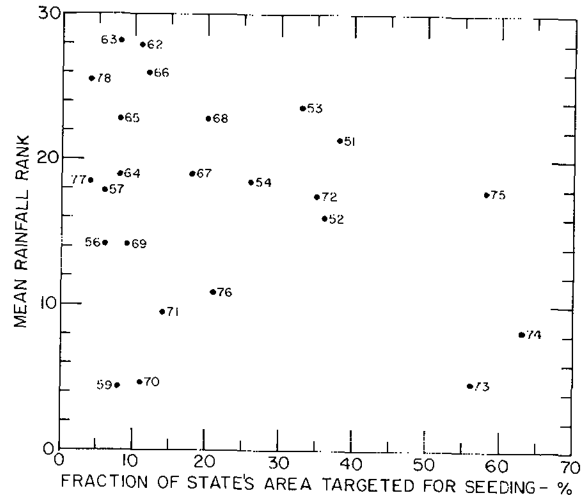

Fig. 4: Mean rainfall rank vs. fraction of the state's area targeted for seeding, 1948-78.

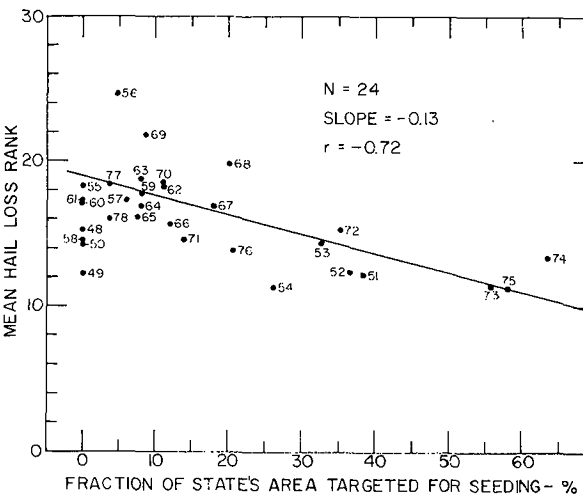

Fig. 5: Mean hail loss rank vs. fraction of the state's area targeted for seeding, 1948-78.

no seeding was done at all. [The correlation coefficient and regression line of Fig. 5 were calculated with the non-seeded years omitted.] This point is discussed in Sec. 5.

In the present study, we have not used control areas from outside South Dakota to evaluate statewide trends. This is a possibility for future investigations of seeding effects upon rainfall, but not as likely for determining effects of seeding upon hail. Wang (1976) found the correlation between hail losses in South Dakota and large parts of neighboring states to be generally small; the best correlations, around 0.7, were found between parts of northeastern South Dakota and parts of southwestern Minnesota, and between southeastern South Dakota and northwestern Iowa.

5. COMPARISON OF EVENTS IN TARGET AND NON-TARGET COUNTIES

A comparison of events in target and non-target counties is meaningful if one assumes that:

1) the effects of seeding are limited to (or at least concentrated in) the target counties; and
2) there are significant correlations between precipitation in target and non-target counties.

For this study, we have ignored county-years involving partial seeding or experimental seeding. The mean rainfall ranks and mean hail loss ranks for years with operational seeding are shown for target counties (with full operational projects) and non-target counties (with no seeding whatever) in Table 1. Years without operational seeding have no entries under target counties, but entries are provided for non-target counties.

The rain and hail loss ranks for target and non-target counties during years with operational projects are compared in Figs. 6 and 7, respectively. The correlation coefficient of the mean rainfall ranks is 0.83, while that for the mean hail loss ranks is 0.64. Both coefficients are statistically significant and justify use of ranks in non-target counties as controls or predictors of the corresponding ranks in target counties. However, because the target counties shifted about from year to year, there is no obvious way to apply the historical regression method. We have therefore adopted simple comparisons, in which a mean rank for non-target counties is accepted as a first estimate of what the corresponding mean rank for the target counties would have been without seeding.

The mean ranks shown in Table 1 for target and non-target counties have been compared to yield the counts shown in Table 2. In 16 of the 25 operational seasons, the average rainfall rank in the target counties exceeded that in the non-target counties. The hail loss ranks were in nearly the same proportion. Assuming a 50% probability that a mean rank for the target counties would exceed the corresponding mean rank for the non-target counties, a draw of 16 to 9 or greater could easily happen by chance. That is, there is no evidence of a net seeding effect under this model.

Distinguishing between ground generator and aircraft seeding leads to a different result (Table 2). The eight ground seasons show no evidence of differences in rainfall or hail losses between target and non-target counties. However, for both rain and hail, 13 of the 17 aircraft seasons yielded a higher average rank in the target counties than in the non-target counties. [The sets of years involved are not identical.] The probability of drawing 13 or more positive results out of 17 is 0.025. This analysis suggests that operational aircraft seeding in South Dakota from 1962 to 1978 tended to increase both rainfall and hail losses. One should not assume that that was the net result, because the analysis gives equal weight to years like 1963 (8% of state seeded) and 1974 (63% seeded). However, the indication of

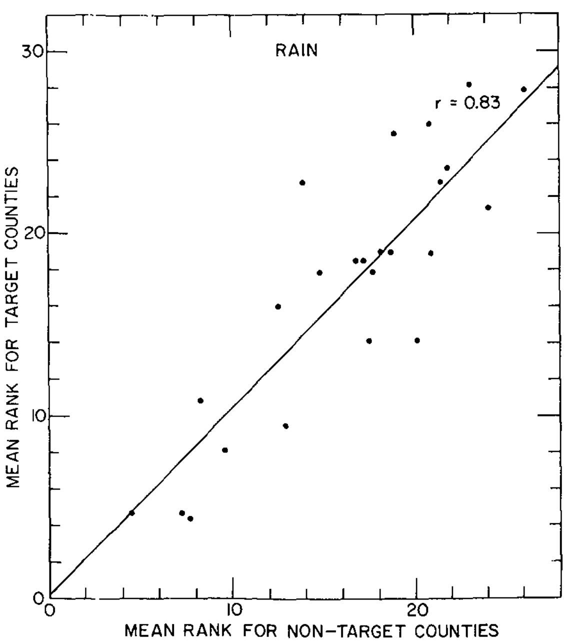

Fig. 6: Scatter diagram of mean rainfall rank for target counties vs. mean rainfall rank for non-target counties.

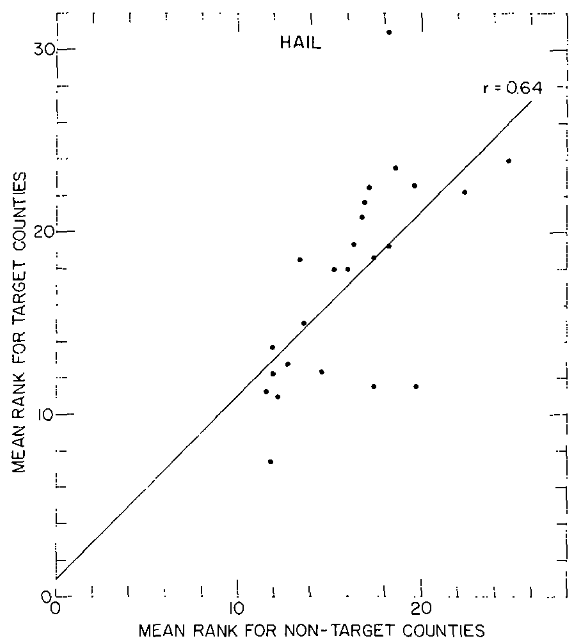

Fig. 7: Scatter diagram of mean hail loss rank for target counties vs. mean hail loss rank for non-target counties.

TABLE 2: Distribution of operational seasons in terms of whether mean ranks for target counties were higher or lower than mean ranks for non-target counties

	Rainfall			Hail Loss Cost		
	Ground	Aircraft	Total	*Ground	Aircraft	Total
Mean Target Rank Higher	3	13	16	3	13	16
Mean Target Rank Lower	5	4	9	4	4	8
Total	8	17	25	7	17	24

*One season (1952) was a tie.

increased hailfall in target counties on certain years merits a closer look, especially as it is consistent with the indication in Fig. 5 that seeding of small areas might have led to increased hail for the state as a whole.[3]

When mean ranks are computed with reference to the target counties only, the regression line on the scatter diagram relating mean hail loss rank to fractional seeding coverage for the state (Fig. 8) has a more negative slope than in the case where non-target counties were included (Fig. 5). The indication of increased hail associated with seeding of small areas is accentuated by limiting attention to the target counties.

Figures 9 and 10, which combine essentially all of the data presented to this point, indicate

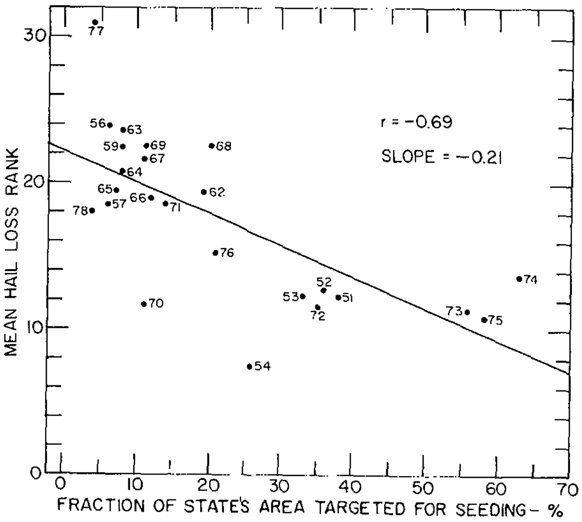

Fig. 8: Mean hail loss rank for target counties vs. fraction of state's area targeted for seeding.

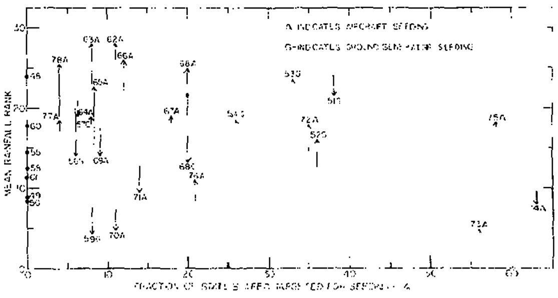

Fig. 9: Mean rainfall ranks in target and non-target counties. [Head of arrow shows mean rank in target counties; tail shows mean rank in non-target counties; G indicates ground generator seeding; A indicates aircraft seeding.]

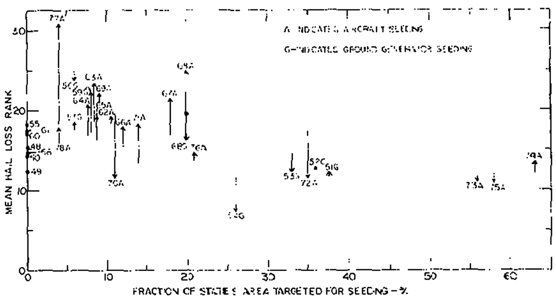

Fig. 10: Mean hail loss ranks in target and non-target counties. [Head of arrow shows mean rank in target counties; tail shows mean rank in non-target counties; G indicates ground generator seeding; A indicates aircraft seeding.]

[3]The analysis includes projects for which hail suppression was not the announced goal. However, it seems that results of all projects should be evaluated in terms of both rain and hail.

that little or no difference in average ranks for target and non-target counties can be demonstrated once the fraction of the state targeted for seeding reaches 40%. Of course, the longer arrows on the left side of Figs. 9 and 10 reflect the greater natural variability of precipitation in small areas, as well as the possibility of differences between seeding effects in target and non-target counties. However, this variability does not account for the fact that most of the arrows on the left side point upward (as they must, to agree with results given above).

We conducted one more study, a permutation test on the hail data in which results were compiled for individual counties, and the years 1972-75 inclusive (the state program) were identified as a special subset of the years with aircraft projects. The procedure for comparing hail damage in a given county (A) to that in any other county (B) was as follows:

1) Calculate the hail loss rank difference (A-B) for each year when County B was not in a seeding program. The years when County B was seeded are considered as missing.

2) Using the Mann-Whitney two-sample rank test, compare the differences for years when County A was in a seeding program (of specified type) to the differences for years when County A was not in a seeding program of any type. Calculate the resultant p-value, using the convention that the p-value increases as the results shift in a direction favorable to County A when it is seeded.

The steps were repeated until County A had been compared to all other counties, at which point an average p-value was computed for County A. The entire process was repeated for all counties that had ever been included in a seeding project of the type under investigation.

The average p-values for individual counties vary widely, but their median holds close to its expected value of 0.50 (Table 3 and Fig. 11). The binomial probabilities for the observed departures of the medians from 0.50 (assuming the average p-values to be independent) are included in Table 3. That for the "Air 1972-1975" category (0.003) indicates a systematic difference between the hail loss tendencies in the target and non-target counties during the years 1972-75 [Fig. 11(b)], but the binomial probability of 0.003 should not be taken at face value as a test of statistical significance because the events in neighboring counties are not completely independent. There are no significant differences for the other categories.

The statistical analyses described above are, in general, rather unusual and have not been subjected to rigorous theoretical inquiry. Certain assumptions may pose problems. While the nonparametric nature of the analyses and the use of permutations should minimize such problems, the possibility of problems should still be kept in mind while interpreting the results.

6. SUMMARY AND INTERPRETATION OF RESULTS

The results of the various tests described to this point can be summarized as follows:

1) For the state as a whole, hail loss decreased as the fraction of the state targeted for seeding increased. However, when small areas were seeded, hail was worse there and, hence, for the state as a whole than on years when no seeding was done at all.

2) Aircraft seeding was associated with increased rainfall and hail loss in target counties as compared to non-target counties.

3) Seeding with ground generators has not produced a detectable difference between target and non-target counties.

4) During the state program of 1972-75, hail losses in target counties tended to be less than in non-target counties.

5) Results for target and non-target counties were not distinguishable in years when the fraction of the state targeted for seeding exceeded 40%.

The overlap among the various data sets makes it impossible to sort out the various effects in an unequivocal fashion. Further subdivision of the data sets, for example, to consider the effect of ground generator seeding directed at small target areas, is not feasible because of sample size limitations. However, by considering these results in the light of those from other cloud seeding operations and experiments on convective clouds, both in South Dakota and elsewhere, some tentative conclusions can be drawn.

TABLE 3

Summary Statistics for Average P-value Samples

Type of Program	Number of Counties	Mean	Standard Deviation	Median	Binomial Probability
Air + Ground	59	0.50	0.18	0.504	0.30
Ground	33	0.50	0.17	0.526	0.15
Air (All)	51	0.52	0.18	0.504	0.29
Air (1972-1975)	50	0.57	0.15	0.557	0.003

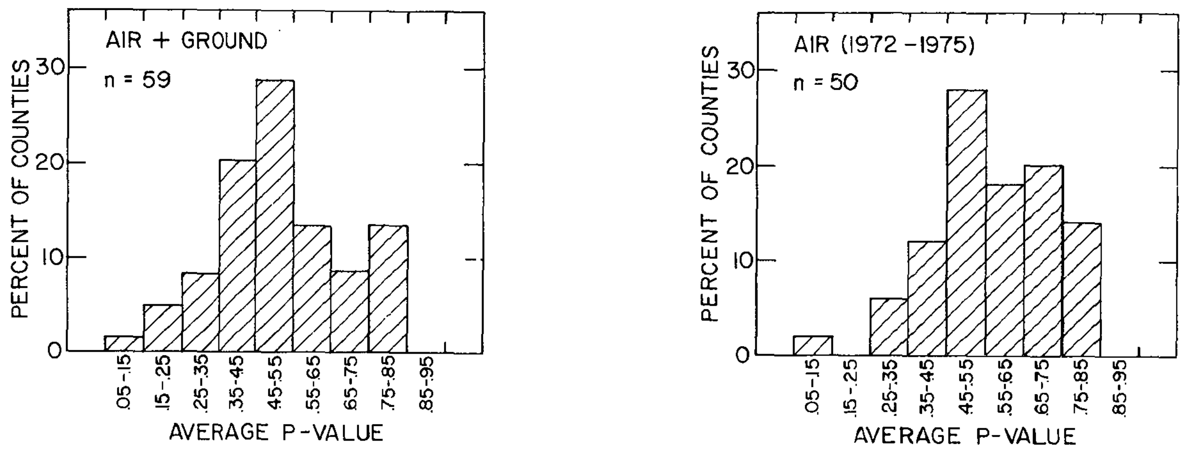

Fig. 11: Distribution of average p-value from comparison of each target county with all non-target counties individually.

Examination of the points in Fig. 9 shows that the generally favorable rainfall result for aircraft seeding (Table 3) is in fact due to projects involving small target areas. The indication that aircraft seeding increases rainfall from convective clouds in small target areas is in line with observations from randomized experiments in South Dakota (e.g., Dennis et al., 1974) and elsewhere, and with the expectations of the project sponsors. It therefore requires no additional comment here.

The rather clear-cut indication that aircraft seeding over small areas has been associated with more hail rather than less in the target counties is surprising. An apparent increase in hail has been observed before in aircraft seeding of single storms or of all storms over small areas (Schleusener and Sand, 1964; Atlas, 1977; Wong and Chidambaram, 1979), but has never been considered statistically significant.

Seeding over larger areas has not given a clear signal on rainfall but appears to have suppressed hail, primarily in the target counties, but in non-target counties as well. The indication that results in target counties become indistinguishable from those in non-target counties once seeding projects expand to cover about half of the state is very reasonable. Especially in 1973-75, the non-target counties constituted isolated pockets (Fig. 1b). As the seeding aircraft often intercepted and seeded approaching storms over non-target counties (Mewes, 1977), and seeding effects are commonly believed to extend some tens of miles downwind from the point where seeding is stopped (e.g., Brown et al., 1969), it is reasonable to think that, for practical purposes, the whole state was seeded during those three years. It was only in 1972, when the northern half of the state was mostly unseeded (Fig. 1a), that a clear-cut distinction between target and non-target counties appeared (Figs. 9 and 10). Therefore the analysis presented in Table 3 appears to have been "carried" by the 1972 results. A rerun of the permutation program for the years 1973-75 only showed no significant difference between target and non-target counties ($P(H_0) = .53$), although the small sample size would have made it hard to demonstrate an effect in any case.

The spreading of seeding effects into non-target counties may explain why ground-generator seeding programs did not produce detectable differences between target and non-target counties. Presumably, targeting is more difficult in the case of ground generator programs than in aircraft seeding programs. This would be especially important as four of the eight seasons with ground generator programs had extensive target areas covering about one-third of the state's total area.

The data provide no indication of seeding effects upon rainfall when a large part of the state is seeded. The low mean rainfall ranks of 1973 and 1974 cannot be attributed to seeding because a large-scale drought affected much of the Great Plains during the mid-1970's. In view of the spread of seeding effects into non-target counties, only the selection of control areas outside South Dakota could provide an analysis with the necessary sensitivity to detect and evaluate the possible effect.

The mean hail loss rank stabilized around 12 in target counties when seeding coverage exceeded 25%, and around the same value over the whole state when seeding coverage exceeded 40%. Computer simulations indicate that a uniform 10% reduction in hail loss reduces the mean hail rank by approximately one unit. Therefore, a reduction in mean hail loss rank to 12 from the expected value of 16 could be due to a uniform reduction of roughly 40% in hail losses. It is not likely, though, that a hail loss reduction would occur in such a uniform fashion. The apparently favorable hail experiences of the early 1950's and mid-1970's could also be due to natural causes, but the lack of any correlation between mean hail loss rank and mean rainfall rank for each year argues against attributing the relatively low hail losses of 1973-75 to the dry conditions prevailing in those years.

7. COULD TARGET SIZE AFFECT RESULTS OF HAIL SUPPRESSION?

The most puzzling aspect of the whole study is the indication that seeding over large areas tends to suppress hail, even though aircraft seeding in small areas was associated with local increases in hail.

The difference in results between the small-scale aircraft projects of the 1960's and the state program of the 1970's could be due to the use of better equipment and seeding techniques during the state-run program. However, this hypothesis does not explain either the apparently favorable hail results from ground generator seeding in the 1950's or the evidence of hailfall increases associated with radar-directed aircraft seeding for hail suppression over a single county in 1977 and 1978. We should be alert to the possibility that the size of the target area matters, perhaps through its impact on the conduct of an operation, or perhaps for more fundamental reasons.

There are precedents for thinking that seeding effects could vary with the size of the target area. Randomized trials to test hail suppression methods on single clouds or small areas have nearly always suggested increases in hail, rather than the anticipated decreases (e.g., Schleusener and Sand, 1964; Schmid, 1967; Atlas, 1977; Wong and Chidambaram, 1979). On the other hand, Changnon (1977) assembled data from several large-area projects, including one randomized project and several operational ones, that provided evidence of net hail suppression effects from AgI seeding from aircraft. Dennis and Schock (1971) noted a general tendency for hail in the vicinity of the randomized crossover Rapid Project to be lighter on days when the project was operational than on days when it was not, even though on each operational day the seed target area tended to receive more hail than the no-seed one. The South Dakota situation bears a resemblance to that in Alberta, where randomized trials have failed to show any reduction in hailfalls from storms seeded by aircraft but where, nevertheless, loss-cost ratios have been consistently smaller throughout the seeded areas during years with seeding than during years without it (Wong and Chidambaram, 1979). The scientists responsible for evaluating the Alberta seeding have pointed out that the year-to-year variations might be due to natural causes or industrial pollution (e.g., Goyer and Renick, 1979), but attributing the observed effects to one or the other of those possible causes rather than to cloud seeding is a judgment call.

One can suggest mechanisms by which AgI seeding could increase local rainfall and hail, and simultaneously suppress hail and, possibly, rain some miles away (e.g., Brown et al., 1969; Dennis and Schock, 1971). However, in view of the wide range of combinations of possible effects and the impossibility of sorting them out on the basis of the data in hand, we shall not pursue that topic. We simply note that, until the matter is resolved, the results of small area experiments like the National Hail Research Experiment can hardly be accepted as a reliable guide to the effects of operational programs covering much larger areas.

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