A TARGET-CONTROL ANALYSIS OF WHEAT YIELD DATA FOR THE NORTH DAKOTA CLOUD MODIFICATION PROJECT REGION

Paul L. Smith, L. Ronald Johnson and David L. Priegnitz
Institute of Atmospheric Sciences
South Dakota School of Mines and Technology
501 E. St. Joseph Street
Rapid City, SD 57701-3995

and

Paul W. Mielke, Jr.
Department of Statistics
Colorado State University
Fort Collins, CO 80521

Abstract. A combined historical/target-control analysis of annual wheat yield data for western North Dakota provides indications of possible seeding effects in the target areas of the North Dakota Cloud Modification Project (NDCMP). The basic analysis procedure comparing post-1975 seeded-period data with pre-1961 non-seeded data gives an estimated yield increase of about 6%, relative to the control area, during the NDCMP operational period. However, the statistical (P-value) indications of the significance of the difference are somewhat equivocal. The historical increase in yields due to improvements in agricultural technology apparently contributes to this difficulty, but an attempt to resolve the issue by redefining the historical reference period to reduce the time gap was unsuccessful.

1. INTRODUCTION

The State of North Dakota has a long history of cloud seeding for the purposes of hail suppression and rainfall increase; a variety of seeding techniques have been used for these purposes. The State-managed North Dakota Cloud Modification Project (NDCMP) was established in 1976, and the treatment strategy has varied little in succeeding years. (There have been some variations in the details of the seeding technology.) Current operational practice is for aircraft to deliver glaciogenic seeding material to summertime convective clouds using guidance from land-based radar (*Boe et al.,* 1990). The target area has varied over the years, but from 1976 through 1988, the continuously participating area included six counties in two districts in western North Dakota.

To ascertain the effectiveness of an operational seeding project such as the NDCMP is difficult. Data acquired during the project specifically to determine effectiveness are often quite limited. Operational project design usually does not include an experimental target/control arrangement or randomized seeding to facilitate statistical evaluation. One must generally make do with the kinds of data available from other sources, and conduct exploratory analyses to find any indications of seeding effects. This typically involves data from a historical non-seeded period and/or a nearby area that can function as a control.

Such an evaluation of the hail suppression effects for the North Dakota operational project was reported in *Smith et al.* (1987a). They based their investigation, hereinafter designated the Hail Analysis, upon long-term crop-hail insurance data and subjected them to statistical methods advocated by *Mielke et al.* (1982). The statistical approach used requires a target and a control area as well as a historical record for each area that extends many years before cloud modification started. This provides a comparison of each area's record during the operational years with the historical record, which helps to mitigate the effect of any long-term trend in either climatic conditions or agricultural technology. For the Hail Analysis, the control area used was the eastern tier of 12 counties in Montana.

Some type of analysis involving precipitation data for the NDCMP operations area would also be desirable. However, the climatic rain gage network in the region is sparse; some counties have only a single station, and there are currently only 18 climatic gages in the six NDCMP target counties of interest. The NDCMP operates a much more dense volunteer-observer gage network, but no historical record preceding the 1976 initiation of the NDCMP is available. Consequently, we turned to crop data as an alternative source of relevant information.

After a working data base was established (Sec. 2), wheat yield data for western North Dakota

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were subjected first to historical (NDCMP-period versus non-seeded period) analyses for the control and target areas separately (Sec. 3), and then to a combined historical/target-control analysis like that described in *Mielke et al.* (1982; Sec. 4). Complications that arose in the course of the latter gave rise to a perceived need to try to incorporate some years with limited seeding prior to the NDCMP operational period (Sec. 5). An attempt to do this (Sec. 6) led to slightly different numerical results but did little to clear up the initial complications.

2. NORTH DAKOTA CROP DATA

The crop data were obtained from the North Dakota Agricultural Experiment Station, Department of Agricultural Economics, North Dakota State University. The basic data were arranged by crop variety. Variables reported for each county were total acres planted, total acres harvested, and bushels produced for each crop variety. Fallowed durum and spring wheat are the dominant crops in western North Dakota, with durum and spring wheat acreages being roughly comparable in the NDCMP target areas and spring wheat predominating elsewhere. Variations among years of 50% or more in planted acreages have occurred in every variety. The present analysis concentrates on total wheat yield, which was determined by combining records from the fallow and continuously-cropped files for spring wheat, durum, and winter wheat. No irrigated-acreage reports were included in the study. The annual average wheat yield for each area of interest was calculated by dividing production (bu) by acres harvested.

Figure 1 is a map of North Dakota indicating the target and control areas for this analysis. The target area comprises the continuously-participating counties of NDCMP District I (McKenzie, Mountrail, and Ward Counties) and District II (Bowman, Hettinger, and Slope Counties). The control area was defined as the remainder of western North Dakota, excluding Adams and McLean Counties (which were part of the NDCMP for some, but not all, of the years included in this study). The total area of the combined target districts is 26,749 km^2, while the control area covers 61,776 km^2. Parts of the control area lie downwind of the target area, so some dilution of any apparent seeding effects because of contamination can be anticipated in the results. We elected not to bring in data from upwind areas in Montana, because of differences in crop reporting procedures between the states. The Appendix gives a table of the annual yield values for the control and target areas.

The years 1935-1951 were initially selected to represent the historical non-seeded period. Limited cloud seeding was reported for years 1952-1967, with more extensive seeding and even some randomization during the period 1968-1975. The NDCMP operational years include 1976-1988. The years 1952-1975 were not included in the historical analysis (Sec. 3) where the NDCMP years were first compared to a historical record from non-seeded years. An initial target-control analysis (Sec. 4) incorporated four additional years (1955, 1956, 1957, and 1960) when no seeding took place. However, in both cases the analysis appeared to be confounded by the changes in agricultural technology over the period involved. Further examination (Sec. 5) indicated that inclusion of at least some of the remaining intermediate years may be necessary to deal with these trends and isolate any signal that could be associated with the seeding operations. A target-control reanalysis of that kind was therefore made (Sec. 6), but the results did not differ greatly from those of the initial analysis.

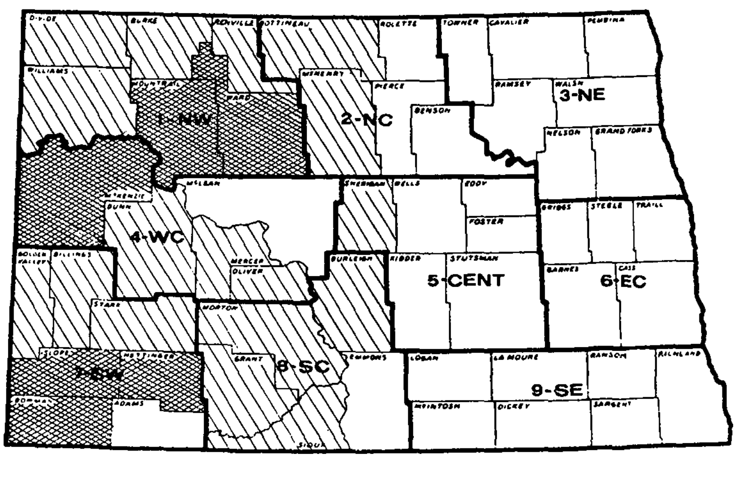

Figure 1: A map of North Dakota showing the location and size of the target area and the control area Unhatched areas were not included in the analyses. Heavy lines delineate climatic divisions of the State.

3. HISTORICAL ANALYSIS

Figure 2 illustrates the historical trends in wheat yield for the target and control areas. A general rising trend associated with improvements in agricultural technology and practices is evident, but there appears to have been a marked overall increase in yields beginning in 1962. This increase, averaging on the order of 10 bu/acre, was sustained through the succeeding years, except for particularly dry ones (1980, 1988).

The control and target values follow each other quite closely for years 1935-1951. Some more substantial differences appear in the intermediate years (1952-1975), with the larger ones generally favoring the target area. The differences show no clear trend for years 1952-1965. From 1966 to 1975, yields of the

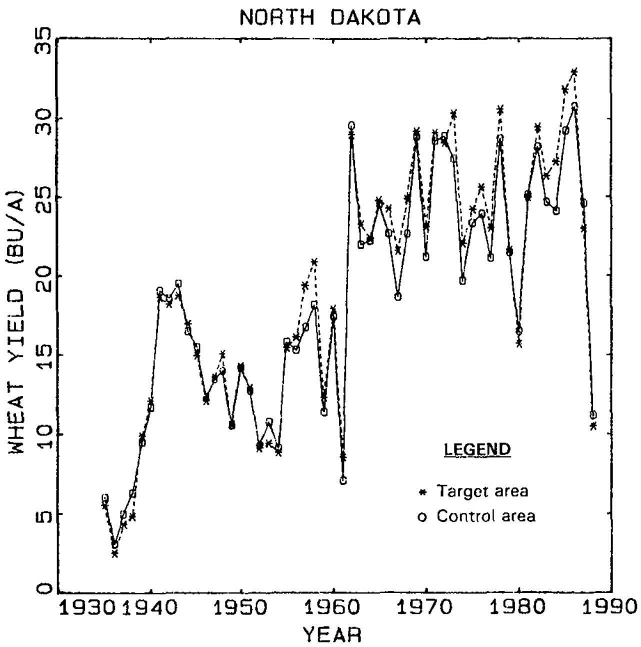

Figure 2: Historical plot of annual wheat yield values for the target area (*) and control area (o). Basic data appear in the Appendix.

target area substantially surpass the control yields in six of the ten years; the remaining four years have yields very similar in magnitude. Thus the overall tendency is for target and control yields to continue to follow one another in the earlier part of the intermediate period, even though some type of cloud modification was being attempted in portions of the target area (except for the four years previously mentioned). From 1966 to 1975, it is clear that target yields predominate. For the NDCMP years 1976-1988, target yields are greater than control yields in eight of the thirteen years. Only in three of the years (1980, 1987, 1988) did control yields exceed target yields, and only the 1987 difference was substantial.

An initial historical comparison of yield values from the non-seeded period (1935-1951) and the NDCMP operational period (1976-1988) utilized a Multi-Response Permutation Procedure (MRPP) test (*Mielke et al.,* 1982a,b) similar to that applied in the Hail Analysis. Separate comparisons were made for the target and control areas. In both instances, the resulting P-value was less than 0.00001, which indicates that the probability of drawing a set of years similar to those of the seeded period at random from the composite group is extremely small. Thus the changes in yield in a given area over time can be considered significant.

However, the well-known contributions of advances in agricultural technology are a major contributing factor which tends to obscure any effects that might be attributed to the seeding operations. The observed historical changes in yield show up in both areas and so could be attributed to those advances without invoking any potential effect of cloud seeding. Consequently, this historical analysis (in contrast to that for the Hail Analysis) provides no clear-cut indications of possible seeding effects. We therefore turned to target-control comparisons as a potential means of compensating for the technological factor.

4. INITIAL TARGET-CONTROL ANALYSIS

The next test involved a target-control analysis like that used in the Hail Analysis; the procedure is described in *Mielke et al.* (1982). These analyses involve MRPP tests of residuals (differences between predicted and observed values) about regression lines on target-control scatter plots. The basic analysis employed here uses the least absolute deviation (LAD) regression line constrained to pass through the origin; this facilitates development of a point estimate for the magnitude of any difference that may be indicated as significant. Similar MRPP tests were also completed for residuals about the unconstrained LAD line and the least-squares regression line.

Each MRPP test compares residuals about the composite regression line for two groups of points, corresponding to the respective time periods. If a low P-value results, it is unlikely that the NDCMP-period residual values correspond to a random selection from the composite group. In such a case, separate constrained LAD lines are determined for the two time periods. The ratio of the slopes of these two regression lines provides a point estimate of the target-control differential change in wheat yield (assumed to be a multiplicative factor) between the two periods. The difference can be regarded as an indication of a possible seeding effect. Other factors may also contribute to the difference, and their contributions would be combined with the seeding effect; the methodology does not permit separating out the individual contributions of any relevant factors. However, we have not identified any factor other than cloud seeding that would be likely to have effects differing between the control and target areas and also differing between the two time periods.

The initial target-control scatter plot for wheat yield is demonstrated in Fig. 3. This figure includes data for all the non-seeded years (1935-51 plus 1955-57 and 1960) and for the NDCMP period (1976-88). The MRPP test on the residuals about the composite constrained LAD regression line gave $P = 0.015$. This is small enough to justify determination of separate constrained LAD lines for the two time periods; those two lines are shown in the figure. The slope for the non-seeded years is very near unity; if soil conditions, precipitation events, and agricultural practices were uniformly distributed across the control and target areas, the idealized slope would be 1.0. Furthermore, the constrained LAD intercept of

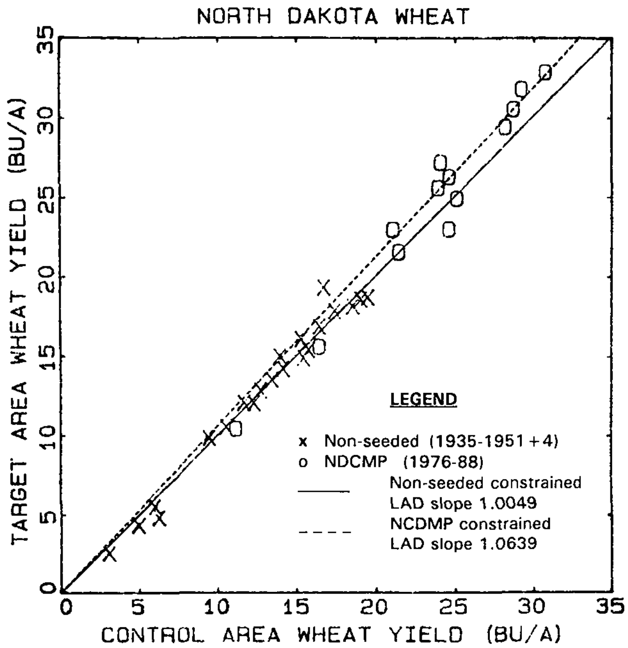

Figure 3: Scatter plot of target vs. control area wheat yields. NDCMP data (1976-88) are indicated by O and constrained LAD regression line is dashed (---------). Non-seeded period data (1935-51 plus 1955-57 and 1960) are indicated by X and constrained LAD regression line is solid (————).

zero would be physically significant as well; if crop yields in the control area were nil, the same would be expected in the target area. The slope for the NDCMP years is somewhat greater; the ratio of the slopes is 1.0639/1.0049 = 1.059, which suggests a relative increase of 5.9% in wheat yield for the target area (as compared to the control area) during the NDCMP treatment period.

However, similar MRPP tests on residuals about the unconstrained LAD line and the least-squares regression line do not indicate any significant difference, with the P-values being approximately 0.57. This is not consistent with the first result, yet there is little difference among the three regression lines. That causes concern about the sensitivity of the analysis procedure to small differences in residuals that are already small because of the extreme linearity of the scatter plot. (In the Hail Analysis, the corresponding plot exhibited much greater scatter and the P-value was small no matter which regression analysis was employed.)

Referring again to Fig. 3, it is evident that the ranges of yield values for the two time periods are essentially separated. Only two of the NDCMP-period points overlap those from the non-seeded period; they correspond to drought years during the NDCMP. The separation is due primarily to the advances in agricultural technology, as discussed in Sec. 3. The consequence is that the two groups of points in essence lie at opposite ends of the regression line. Small changes in the line used (and especially in its slope) therefore can have different effects on the already small residuals for the different groups. The linear correlation is quite high (r = 0.99), but the extreme linearity of the data in this case may be detrimental to stability in the residuals under different regression procedures and in the corresponding calculation of the P-value. A possible means for overcoming this complication would be to enhance the overlap between the two data groups on the scatter plot.

5. REDEFINITION OF THE HISTORICAL PERIOD

It appeared plausible that the general separation of the data groups appearing in Fig. 3 could be mitigated by inclusion of data from more of the intermediate years between 1951 and 1976 in the "non-seeded" set. The frequency distributions of wheat yields for the control and target areas for all years 1935-1988 are presented in Fig. 4 as histograms. Extreme values are more prevalent for target yields, but most of the yield values fall between 10 and 30 bu/A. In Fig. 3, the lack of non-seeded data points above 20 bu/A is a significant feature. The

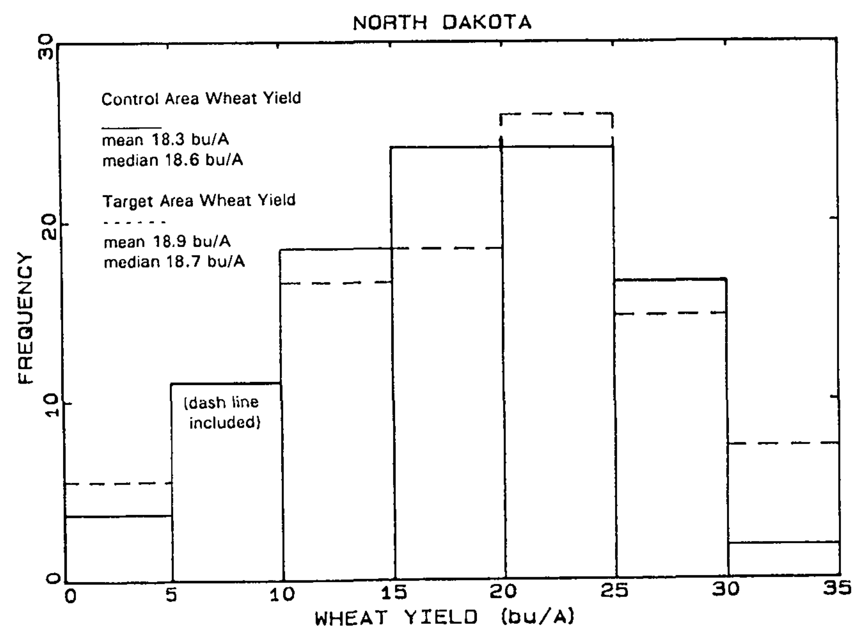

Figure 4: Histograms of wheat yields for the control area (————) and target area (---------) for years 1935-88. Control area mean is 18.3 bu/A and median is 18.6 bu/A; target area mean is 18.9 bu/A and median is 18.7 bu/A.

frequency distributions show that 48% of the target yields and 43% of the control yields are greater than 20 bu/A. Figure 2 shows that all but one of those cases occurred in the post-1961 period. Thus, inclusion of additional intermediate years (especially ones from 1962 onward) would provide greater overlap between historical and NDCMP years, which might mitigate the apparent sensitivity to small changes.

Some seeding to modify clouds occurred in most of the intermediate years between 1951 and 1976, with the level of activity building up erratically over the period. Appendix A of the report by *Smith et al.* (1987b) gave numerical values for the fraction of the target area actually seeded. These values are reproduced in Fig. 5 and are represented by the dashed line. Since some seeding was accomplished during the intermediate years, inclusion of some of those years into the historical (and ideally non-seeded) set could have the effect of diluting any statistical differences between seeded and historical sets. Therefore, only years that are not statistically different from the ones known to be non-seeded were incorporated into the redefined "historical" data set.

The dividing point was established by making a running determination of another P-value based on residuals about a LAD regression line constrained to pass through (0,0). The 21 years of non-seeded wheat yields were compared to yields from subsets of the remaining intermediate years (1952-1975 minus the four non-seeded years). This comparison began by using a subset consisting of the yields for just the year 1952, and determining the composite constrained LAD line for the 22 data points of target versus control yields. The P-value was determined from an MRPP test based upon the residuals from that line, with comparison of the 21 non-seeded years to the one-year subset from the remaining years. The process was then repeated with the subset incremented through addition of the wheat yields from the next intermediate year (1953). This procedure was continued, incrementing the intermediate subset one year at a time, through year 1975.

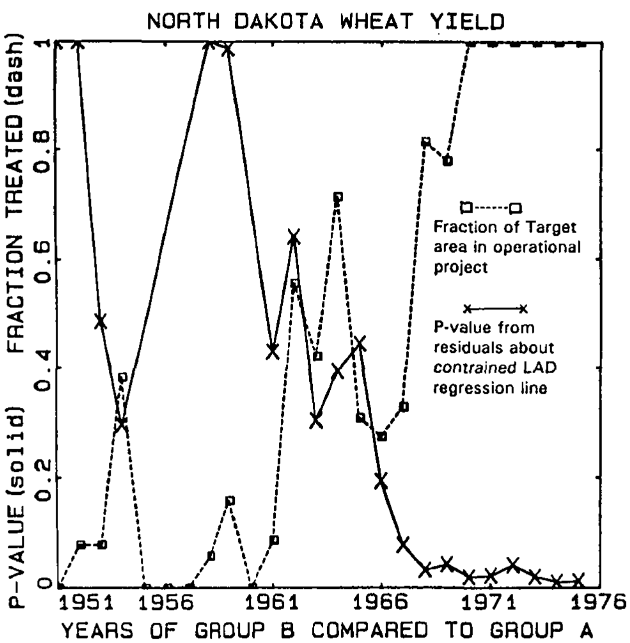

Figure 5: Plot of P-value (x——x) from MRPP test based on residuals about constrained LAD regression line vs. cumulative years of intermediate set considered, in comparison to the non-seeded group. The dashed line (□-------□) represents the fraction of the target area seeded, by year.

The resultant series of P-values is represented in Fig. 5 by the solid line. A general downward trend in the P-values is apparent as additional years are incorporated into the subset of intermediate years. This implies that the subset becomes noticeably different from the non-seeded years as additional years are brought in -- an indication already apparent from Fig. 2. Any selection of a demarcation point is somewhat arbitrary, but we chose the point where the P-value drops below 0.1 for this purpose. Using $P \geq 0.1$ as the criterion results in eleven intermediate years (1952-1966, except for the four non-seeded years) being grouped with the 21 non-seeded years into the redefined historical group. The remaining nine intermediate years (1967 and beyond) correspond to increased seeding efforts in the target area and are hereafter referred to as the "mid years"; the fraction of the target area seeded increased to 100% during this period.

It is the cumulative effect and not the contribution from any one year that determines the P-value. Thus yields for 1966 and perhaps a preceding year or two may more appropriately belong to the mid year subset rather than to the "non-seeded" intermediate subset. In this sense, the present analysis procedure is somewhat conservative and will tend to dilute any indications of seeding effects.

6. TARGET-CONTROL REANALYSIS

The combination of target and control wheat yield values for years 1935-1966 is henceforth taken to represent the historical trend. This redefined historical period was compared to the NDCMP years (1976-1988) and also to the remaining mid years (1967-1975). Table 1 gives the results of the various regression analyses and comparative P-values from MRPP tests of the appropriate groups of residuals. For the truly non-seeded years (1935-1951 plus 1955-57 and 1960), the constrained LAD regression for target versus control yielded a slope of 1.00494. Adding the subset of intermediate years to the historical set changed the constrained LAD slope only slightly, to 1.00743.

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TABLE 1

Regression Parameters and Comparative P-values for Various Target-Control Comparisons

COMPARISON	(NDCMP)	(Mid)	(Historical)	NDCMP / Historical	Mid / Historical	NDCMP / Mid	Mid + NDCMP / Historical
No. of Years	13	9	32	45	41	22	54
Least Absolute Deviation (through origin)							
Intercept	0	0	0	0	0	0	0
Slope	1.06387	1.03614	1.00743	1.02589	1.01778	1.06387	1.02675
Σ Res	13.35	11.01	22.59	40.66	35.27	24.36	52.11
P-value				0.047	0.009	0.538	0.007
Least Absolute Deviation (free)							
Intercept	-2.31588	6.71746	-0.71375	-1.07264	-0.78337	0.52243	-0.94373
Slope	1.14492	0.77795	1.05535	1.09195	1.06973	1.04567	1.08008
Σ Res	11.19	4.77	22.02	35.73	34.09	24.33	47.77
P-value				0.846	0.096	0.562	0.175
Least Squares							
Intercept	-2.63342	6.44146	-0.39248	-0.82823	-0.43961	-0.13958	-0.68366
Slope	1.15277	0.79677	1.04076	1.07342	1.05546	1.05587	1.07039
Σ Res	11.52	5.22	22.54	35.89	35.13	25.09	48.55
r	0.98	0.97	0.99	0.99	0.99	0.97	0.99
P-value				0.453	0.058	0.558	0.106

NDCMP: 1976-88
Mid: 1967-75
Historical: 1935-66

Three types of regression analysis were again applied in all cases: The LAD line constrained to pass through the origin, a free LAD line, and traditional least-squares regression. The comparison of the NDCMP to the historical period in Table 1 shows a significant (i.e., small) P-value for the constrained LAD analysis, but unconstrained LAD and least-squares results indicate that in those cases the two groups of residuals belong to a common class. Essentially the same finding resulted from the initial analysis in Sec. 4, so adding the eleven years of data from the intermediate period to the historical group has not clarified the results in this respect.

Figure 6 illustrates the NDCMP versus historical comparison. The inclusion of the subset of intermediate years in the historical set has indeed reduced the separation between the two groups of years on the scatter plot. Again, the historical constrained LAD line (solid) is very near the 1:1 line, while the constrained LAD line for the NDCMP years (dashed) has a greater slope. The ratio of the slopes (1.0639/1.0074 = 1.056) indicates a 5.6% yield increase for the NDCMP years. Thus the inclusion of the subset of intermediate years (which involved some seeding activity) may have reduced the separation between groups, but it produced essentially no change in the magnitude of the apparent difference obtained from the basic constrained-LAD analysis. As noted above, it also did not succeed in producing consistent P-values for the comparisons of residuals about the different regression lines.

The comparison between the historical period and the remaining nine years of the intermediate period is also interesting. Those "mid years" (1967-1975) are apparently distinguishable from the historical set, as indicated by the magnitudes of the P-values in Table 1. No matter which regression line is used to calculate the residuals, the P-value remains below 0.1. Figure 7 presents the historical and mid year data sets with their respective constrained LAD lines. The MRPP P-value is small (0.009), yet the slopes of the two lines differ only slightly. The ratio of the slopes (1.0361/1.0074 = 1.028) indicates a wheat yield increase in the target area of about 2.8% for the nine mid years. Thus for this comparison we find a stronger and more consistent statistical indication of a difference, but the apparent difference

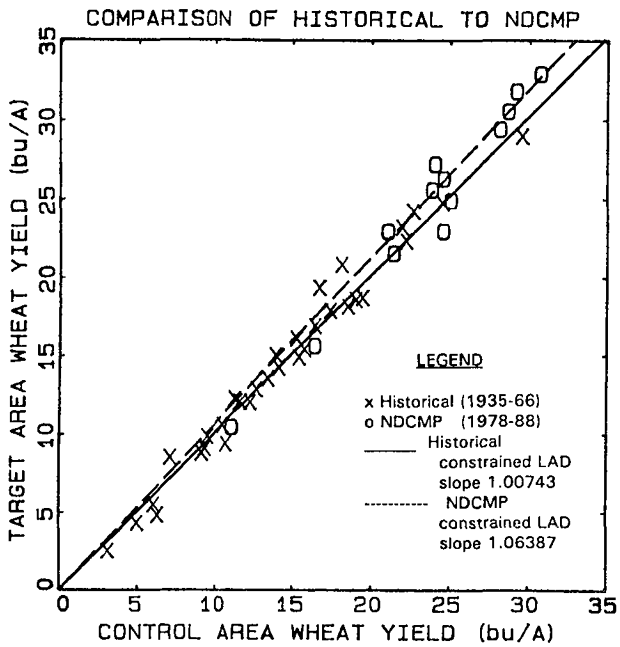

Figure 6: Scatter plot of target versus control area wheat yields. NDCMP data (1976-88) are indicated by O and constrained LAD regression line is dashed (---------). The data for the expanded historical set (1935-66) are indicated by X and constrained LAD regression line is solid (————).

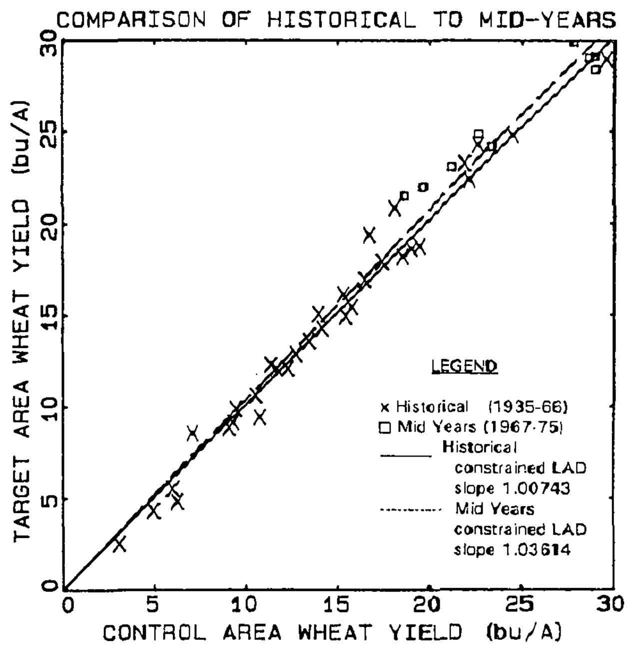

Figure 7: Scatter plot of target vs. control area wheat yields. Data for mid years (1967-75) are indicated by □ and constrained LAD regression line is dashed (---------). Data for expanded historical set (1935-66) are indicated by X and constrained LAD regression line is solid (————).

is smaller in magnitude. The latter would be consistent with the lower level of seeding activity during the mid years (Fig. 5) and with a general improvement of operational procedures during the NDCMP period. The strength of the analysis method is indicated by the fact that such a small difference is found to be significant.

For completeness, two further comparisons were made. First, the NDCMP years were compared to the mid years to evaluate any difference between the two periods, each of which involved fairly extensive seeding activity. Again Table 1 shows similar, but this time large, P-values no matter which type of regression is used. (It is also interesting to note that the constrained LAD line slope is identical to that for the NDCMP years by themselves.) Thus the nine mid years cannot be distinguished from those of the NDCMP according to this test. This finding is not incompatible with the fact that the point estimates of target-control differences in yield for the two periods are not the same; the confidence intervals for those estimates (which cannot be determined by the present analysis procedure) may well overlap.

All the seeded years (1967-1988) were then compared to the historical set; the last column of Table 1 presents the results. The basic results are similar to those for the NDCMP-vs.-historical comparison (fourth column of the table), although the P-values in the last column are all lower. The disparity among P-values for the various regressions of NDCMP versus historical periods may be due to the effects of some especially dry years during the NDCMP. According to Fig. 2, yields from the target area were less than those from the control area for NDCMP years 1980, 1987, and 1988. The years 1980 and 1988 were extremely dry in western North Dakota and the yields were low, being comparable to those from the period before 1962. Typically during the NDCMP, when the yields are higher, the target yields exceed those of the control area. The drought in 1980 and 1988 may have affected the target area more strongly than the control area, perhaps by restricting the number of opportunities for effective cloud seeding.

7. CONCLUSIONS

1. The comparison shown in Fig. 3 for the NDCMP years versus the non-seeded years indicates a 5.9% wheat yield increase in the target area (as compared to the control area) for the NDCMP years. The non-seeded data set for this comparison specifically excluded years with any known cloud modification treatments. The MRPP P-value for the basic constrained-LAD regression analysis was 0.015, which suggests a significant difference between the two groups of years. However, much higher P-values resulted when other regression lines were used in a similar type of analysis, so the statistical support for a difference is somewhat equivocal.

2. The general increase in wheat yields over the years, due primarily to advances in agricultural technology, complicates the problem of isolating differences that could be related to the seeding. Because of this trend, the yield values for the non-seeded and NDCMP years are almost completely separated on the target-control scatter plot of Fig. 3. That may contribute to the lack of consistency in the P-value determinations under different regressions.

3. Expanding the historical data set to include a subset of the intermediate years, when limited seeding activity was being carried out in the target area, had the expected effect of decreasing the separation between historical and NDCMP yields. The point estimate of the apparent seeding effect for the NDCMP was essentially unchanged, but the statistical support for a difference was not clarified as had been hoped.

4. The scatter plots for these analyses are extremely linear, with target-control correlation coefficients ranging from 0.97 to 0.99. The residuals, which are calculated as the differences between regression-predicted and observed values, are correspondingly small. Thus, the P-values resulting from the MRPP tests are based upon small differences among small residuals. Even so, the analysis method was able to provide statistical support for a 2.8% target-area yield increase for the mid years when compared to the expanded historical data set. Thus, the method can be sensitive to small differences.

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APPENDIX

Annual Wheat Yield Values (bu/A) for Control and Target Areas

Year	Control	Target
1935	6.01	5.49
1936	3.06	2.49
1937	4.95	4.30
1938	6.27	4.80
1939	9.47	9.85
1940	11.68	12.07
1941	19.04	18.59
1942	18.55	18.16
1943	19.48	18.72
1944	16.45	16.89
1945	15.44	14.89
1946	12.30	12.06
1947	13.45	13.55
1948	13.96	15.01
1949	10.54	10.57
1950	14.16	14.23
1951	12.73	12.87
1952	9.30	9.10
1953	10.77	9.40
1954	9.10	8.79
1955	15.77	15.40
1956	15.30	16.08
1957	16.73	19.34
1958	18.14	20.82
1959	11.38	12.27
1960	17.42	17.87
1961	7.07	8.50
1962	29.56	28.96
1963	21.96	23.23
1964	22.22	22.34
1965	24.54	24.76
1966	22.67	24.24
1967	18.65	21.52
1968	22.64	24.85
1969	28.84	29.16
1970	21.16	23.06
1971	28.56	29.07
1972	28.87	28.43
1973	27.42	30.30
1974	19.64	21.99
1975	23.32	24.17
1976	23.90	25.59
1977	21.06	22.96
1978	28.70	30.53
1979	21.42	21.55
1980	16.43	15.62
1981	25.09	24.91
1982	28.18	29.42
1983	24.64	26.30
1984	24.08	27.21
1985	29.22	31.79
1986	30.73	32.86
1987	24.58	22.96
1988	11.15	10.45