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AN EVALUATION OF WEATHER MODIFICATION ACTIVITIES IN THE TEXAS HIGH PLAINS

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FOREWORD

This report on important original research into the effects of hail suppression projects on the Texas High Plains is being published unrefereed by the Texas Water Development Board at this time in order to make the authors' findings available to the scientific community and the general public as soon as possible after completion of the research effort. This report is not intended to replace the kind of scientific publication which would result from colleague review or complete refereeing, nor is it in any way an expression of the views or policies of the Texas Water Development Board.

Potential hail producing clouds were seeded with silver iodide (AgI) from an airborne platform by release of the seeding materials into the updraft portion of the subcloud atmosphere. The cloud seeding projects evaluated were carried out during the spring-summer-fall seasons by commercial operators employed over the four-year period 1970-73 by Better Weather, Incorporated, of Littlefield, Texas and Plains Weather Improvement Association, of Plainview, Texas. The evaluation being reported on was performed by a team of scientists from Texas A&M University, q.v., under a contract awarded them in 1974 by the Texas Water Development Board.

TEXAS WATER DEVELOPMENT BOARD
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ABSTRACT

This report presents results of a study to evaluate the effectiveness of cloud seeding in the Texas High Plains for the months of May through October during the 4-yr period 1970-73. The effects of seeding on rainfall are examined graphically, and on both rainfall and hail by the analysis of variance method and the chi-square goodness-of-fit test. The amount of damage to cotton is taken as the primary indicator of weather damage.

Statistical analyses of rainfall data indicate that cloud seeding does not influence rainfall. Also, a statistical analysis of cotton losses attributable to hail and insurance damages paid due to hail damage on cotton indicates that the hail suppression program did not significantly affect cotton hail damage.

The outline of an operational, one-dimensional, numerical model of hail producing thunderstorms was developed to study the possibility of predicting the occurrence and severity of hailstorms. No relationship could be ascertained between radar-echo coverage and such severe-weather phenomena as hailstorms, tornadoes, and funnel clouds.

There are several limitations of the data used in the statistical analysis of this study which must be understood and considered in the interpretation of the results. These are: 1) the ASCS data reflect total crop losses due to weather, while the loss due to hail alone is unknown, 2) the official rain gages are sparse and inadequate for an adequate determination of the areal distribution and amount of rainfall, 3) hail occurrences before the seeding period were not used in the analysis, and 4) the weather-related losses to crops established by county ASCS offices are based to a large degree on the producer's established average yield although major weather factors were listed.

ACKNOWLEDGMENTS

In our effort to evaluate the effect of hail-suppression activities on the Texas High Plains, we have received, in most cases, exceptionally good cooperation. The Crop-Hail Actuarial Association provided published statistics for private crop insurance companies, the Federal Crop Insurance Corporation made special computer runs to provide statistics relative to federal crop insurance and the U.S. Department of Agriculture, and the Agricultural Stabilization and Conservation Service (ASCS) released their data on producer weather losses. We are especially appreciative to the High Plains County ASCS offices for their kindness and cooperation.

The authors of this report extend their sincere appreciation to graduate students Gary Condra, Fred Proctor, and Jane Lamb for their invaluable assistance, and to Dr. Rudolf Freund who assisted in the statistical evaluation of the data.

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CHAPTER I. INTRODUCTION AND BACKGROUND

Rainfall and hail assume roles of crucial importance in the High Plains area of Texas, where seven drouths have occurred since the turn of the century and violent, destructive hailstorms ravage the area every year. Indeed, rainfall and hail become the determinants of survival for many dry-land farmers in West Texas. Attempts to modify the weather have attracted much attention in the Plains area during the past 10 yr, where some six million acres are cultivated annually for the production of cotton, grains, and other farm commodities. As a consequence, an accurate assessment of the measure of success or failure of weather modification attempts is essential for planning the future course of weather modification in Texas.

Because of the high risk of hail damage to cotton and other crops in the High Plains, a number of farmers organized in 1970 to sponsor an undertaking to prevent or reduce the occurrence of hail by seeding clouds from aircraft. Participation in the endeavor was sufficient to permit the mounting of a technically sound cloud-seeding operation in Hale County. Three years later farmers in adjacent Lamb County launched an essentially identical program. The two groups coordinated their operation to prevent duplication. Briefly stated, the operation consisted of locating incipient convective clouds by means of a ground radar and guiding a seeding aircraft to each rain cloud before it reached hail stage. The airplane released silver iodide particles from wing-mounted spray guns while flying at the base of the cloud. Theoretically, the silver iodide was to have risen in the cloud to the freezing level. At that level it served to nucleate the formation of countless ice crystals, which consume the available water instead of allowing it to form large hail kernels.

Now interest has shifted to the question of whether or not the suppression of hail also suppresses rainfall. To investigate the possible effect cloud seeding may have on rainfall, an area of 14 High Plains counties was chosen for this study. The area under consideration includes, in addition to the seeded counties, Hale, Lamb, and Floyd, 11 adjacent counties encompassing the seeded region. It lies between approximately 33°N and 35°N and is bounded east and west be 101°W and 103°W.

The region being investigated is part of the largest level plain of its kind in the United States. The elevation of the region changes gradually from 640 m above mean sea level in Crosby and Briscoe counties in the east to 1342 m in Bailey county along the New Mexico border. The eastern extremity of the region is characterized by the Cap Rock Escarpment--a striking surface feature that runs as an east-facing mountain wall through Briscoe, Floyd, and Crosby counties. The counties being considered in this study are fairly uniform in size, the difference in area between the largest--Lamb--and the smallest--Cochran--being only 620 km^2. Many of the counties are roughly square, the average size being 2340 km^2.

An agricultural economy prevails throughout most of the area. Chiefly due to the climate and resultant agriculture, the study region is subdivided into the North Plains and South Plains. From Hale county north, the North Plains sector has primarily grain sorghum and wheat farming, with some significant ranching and petroleum developments. The South Plains, of which Lubbock is the principal city, leads Texas in cotton production. From underground reservoirs, irrigation which is centered around Lubbock and Plainview, provides water for much of the crop acreage. Of Texas' approximately 11.8 million population, 343,000 or 3 per cent, live in the High Plains area under study (The Texas Almanac, 1974-75).

The climate of the South Plains region of Texas is semiarid in nature and serves as a transition between desert conditions to the west and humid subtropical conditions to the east and southeast. The prevailing wind direction is southerly over the entire area during the spring and summer months, and during the fall and winter seasons the region is influenced by a wind flow generally from the west or southwest. Mean wind speeds are rather high, since the surface does not offer as much resistance to wind movement as in areas where taller plant cover and more uneven topography prevail. The stronger continuous winds occur in late winter and early spring, while wind speeds are highest but of short duration during intense thunderstorms. A region once notorious for its frequent duststorms, the South Plains in recent years have suffered fewer duststorms because of improved tillage methods.

In general, the wet season in the South Plains of Texas occurs during the summer months, when warm, moist, tropical air is carried inland from the Gulf of Mexico. This subtropical airflow frequently produces moderate to heavy afternoon and evening thunderstorms, some of which are so violent as to beget hail, high winds, and tornadoes. Precipitation in the area is characterized by its erratic nature. There have been occasions when rainfall in the "dry" season exceeded that of the "wet" season. The dry and wet seasons are not distinct, for at times wet periods occur in the dry season and dry periods in the wet season.

Several dominant macroscale systems account for most of the rainfall observed in the South Plains. The seasonal variation of rainfall may be due to: (1) the orientation of the general, low-level wind flow with respect to the Gulf Coast; (2) the position of the upper atmospheric jet stream with respect to latitude; (3) the invasion of polar air masses from the Arctic during much of the year; and (4) the presence of a variety of mesoscale systems, many of which are generated from convective heating in the warmer seasons of the year.

A. OBJECTIVES

The primary objective of this research was to evaluate the effectiveness of cloud-seeding activities in the Texas High Plains in terms of the prevention or reduction of hail and the influence of seeding upon rainfall.

The study investigated the distributions of hail and monthly rainfall in the High Plains and provided statistical analyses of the variability of hailstorm and rainfall occurrence.

Two approaches have been followed in the analysis of the data, viz., qualitative and quantitative. The qualitative approach consists of a graphical analysis of rainfall data from which conclusions are drawn about the effectiveness of seeding. The quantitative approach employs the analysis of variance method to evaluate the effectiveness of seeding upon both hail and rainfall.

An operational prediction model for the occurrence and severity of hailstorms is developed to further an understanding of those atmospheric conditions most receptive to effective cloud-seeding activities. Radar-echo sketches are examined for possible association between some radar-echo parameter, such as number of radar echoes or the area covered by those echoes, and precipitation and other significant weather phenomena.

B. A REVIEW OF THE LITERATURE

A search of the literature on cloud-seeding activities reveals that the effects of cloud seeding remain a source of controversy among meteorologists and agronomists. The arguments for and against weather modification have been as stormy as the necessary atmospheric conditions themselves. The basis for cloud modification was established in the 1930's when investigators Bergeron and Findeisen, acting on a suggestion by Wegener (1911), promoted a theory of rain formation based on the coexistence at the same temperature of supercooled water droplets and ice crystals in convective clouds (Fleagle, 1969). Scientists of General Electric Company in 1948 provided the first distinct evidence that silver iodide smoke could modify natural supercooled convective clouds (Mason, 1962). It was discovered that solid CO_2 (dry ice) rapidly transformed supercooled water droplets into ice crystals when the ice was dropped into supercooled convective clouds (Matthews et al., 1971).

The National Academy of Sciences (NAS) (1973), in a comprehensive review of all weather modification activities performed prior to 1966, reports, "There is increasing but still somewhat ambiguous statistical evidence that precipitation from some types of cloud and storm systems can be modestly increased or redistributed by seeding techniques." After conducting extensive investigations into modification programs carried our since 1966, the NAS panel was able to substantiate the conclusion cited above and offer some elaborations of that conclusion:

> The panel now concludes on the basis of statistical analysis of well-designed field experiments that ice-nuclei seeding can sometimes lead to more precipitation, can sometimes lead to less precipitation, and at other times the nuclei have no effect, depending on the meteorological conditions. Recent evidence has suggested that it is possible to specify those microphysical and mesophysical

> properties of some cloud systems that determine their behavior following artificial nucleation. A related problem that has come into sharper focus is to ascertain if, and under what conditions, the seeding of clouds in one area will modify precipitation amounts in another area.

Commercial cloud seeding had its beginning in the United States in the late 1940's in response to the public interest evoked by the findings of the General Electric Company experiment and the optimistic claims these findings created. Cloud seeding operations flourished in many areas of the country; at one point in the early 1950's, 10 per cent of the total land area in the country was involved in commercial seeding programs (Fleagle, 1969); this was during a particularly severe drouth in the Southwest.

Various experiments that have involved randomized seeding of convective clouds have been performed over the past two decades with contrasting results. One of the more prominent, Project Whitetop, was conducted on summer cumulus clouds by the University of Chicago in the early 1960's. Results of that study indicate that, in the primary seeding areas, there was 30 to 40 per cent less rainfall on seeded days (Neyman, 1969). These results were found to be statistically significant. Furthermore, smaller reductions in rainfall that were also statistically significant were observed outside the target area where seeding effects were not anticipated.

Gelhaus _et_ _al_. (1974) reported that, in a randomized cloud seeding project in northwestern South Dakota, an examination of rainfall data gave evidence that rainfall changes in both seeded and non-seeded areas were different as a result of natural processes affecting large areas, and the differences could not be attributed to cloud seeding.

Henderson (1974) examined monthly precipitation values of paired counties in the Texas High Plains and found that the observed rainfall in the seeded region did not depart significantly from the expected values. He concluded that rainfall within and adjacent to the target region was not modified significantly by cloud seeding.

Through the use of correlation coefficient analysis in a study of rainfall variations in Oklahoma, Pybus and Hughes (1973) found that, in any given year at a given station, the amount of variation in rainfall due to seeding is much less than would be expected from year-to-year under normal, unmodified conditions. Their investigation showed that a 10 per cent change in measured rainfall, at a given station, can be detected by using techniques of gradient analysis at the 20 per cent confidence level.

Huff and Changnon (1972) studied the effects of cloud seeding on agricultural production and found that some crops would be benefitted in most of the growing seasons through a cloud seeding program, although the reaction to seeding varied substantially between regions. However, it was found that the effectiveness of seeding varied considerably from year-to-year due to the variability in the natural distribution characteristics of storm and daily rainfall.

Other experimental programs have concluded that seeding has increased precipitation at the surface. Weinstein (1972) demonstrated the potential of precipitation enhancement by ice-phase seeding of isolated convective clouds in the western United States. Even though atmospheric conditions were favorable for seeding with ice crystals only 25 per cent of the time, results indicated that seeded clouds could have been made to yield approximately 50 per cent more than those neighboring convective clouds not seeded.

Woodley (1970) showed that precipitation from isolated convective clouds can be increased significantly through judicious seeding of the right clouds on the right day. He proved the possibility of boosting rainfall amounts by as much as 300 to 500 per cent from isolated convective cloud systems in South Florida and Arizona.

Ogden and Jayaweera (1971) studied the shape of daily rainfall frequency distributions during a cloud seeding experiment in Australia and found evidence suggesting that seeding is more effective in increasing moderate rainfall than in affecting light or heavy rainfall. They found that cloud seeding consistently increased rainfall on days when the area rainfall averaged 0.1 to 0.5 in.

In some seeding experiments, investigators have found that results depend on the specific meteorological conditions involved. Mielke _et_ _al_. (1970) reported that the effectiveness of ice-nuclei seeding depends on cloud-top temperatures as well as on wind speeds at middle layers in the atmosphere. Simpson (1972) disclosed that some frontal conditions appeared suitable for cloud seeding, thereby indicating the hope that dynamic seeding techniques may be successfully extended into dry periods.

In a very important discovery, Simpson (1972) found that both seeded and non-seeded rain populations can be fitted by a gamma distribution, namely,

$$P(R) = \frac{\beta^{\alpha}}{\Gamma(\alpha)} R^{\alpha-1} e^{-\beta R} \qquad (1)$$

where $P(R)$ is the probability density of a rainfall amount R from a single cloud. The parameter α determines the shape of the distribution and the scale is determined by β; Γ is the gamma function. Simpson's study showed that seeding does not affect appreciably the shape or coefficient of variation of the rainfall distribution but merely advances the mean of the transformed data by some factor. That is to say, the seeded population has a higher mean and a higher standard deviation than the unseeded population.

Hail suppression activities in the U.S. often have been plagued with the same controversies and questionable results characteristic of rain-enhancement studies. Many hail-suppression studies have been limited in scope because of the scarcity of available data. Changnon and Schickedanz (1969) found that hail data in Illinois had a high degree of areal and spatial variability. Despite this limitation, however, they reported that the data could be utilized in planning and designing hail modification experiments. Their study showed that 40 per cent reductions in the number of observed annual hail days may be detected within a period of as little as 3 yr or less.

A greater understanding of the climatology of any given area reveals a close relationship between summer hail patterns and associated climatological events. Huff (1964) showed that the areal distributions of mean maximum temperatures, mean noon dew-point temperatures, normal rainfall, and the number of surface fronts together explained between 56 and 90 per cent of the variations in hail patterns.

The complexity of the evaluation problem in hail-suppression studies has led to questionable results in most studies attempted during the last decade. For example, Changnon and Henderson (1974), using hail-day records provided by the National Weather Service, found an insufficiency of point hail-day data and, consequently, no strong conclusions as to a reduction in number of hail days. He noted that a single, point source of data in one target county limits to a large degree any evaluation of the hail experienced in that county.

Changnon (1969) suggested that preliminary statistical studies concerning the type of data collection, size of study area, statistical design, and duration of hail suppression experiments should be performed prior to actual experimentation.

Just recently experiments have been conducted to evaluate the effects of seeding winter clouds on snowpacks in the high mountain areas of the Western U.S. Weisbecker (1974), in a study of seeding activities in the Upper Colorado River Basin, revealed an increase due to seeding of 20-25 per cent in snowfall at elevations above 9000 ft. He indicated that this increase in snowfall caused by seeding would be the same in any season, wet or dry. Furthermore, he found that cloud seeding increases the duration of snowfall, not the intensity.

CHAPTER II. DATA BANKS UTILIZED

A. METEOROLOGICAL DATA

Historical records of precipitation, including hail, as measured or observed and reported at regular and cooperative stations of the National Weather Service were obtained. The Office of the State Climatologist of Texas A&M University provided the climatological source materials for the study. Initially, to assist the statistical aspect of the evaluation of results of cloud seeding on hailstorm phenomena, data relating to hailstorm occurrences were extracted from climatological records. The data, obtained from "Severe Storm Files" of the State Climatologist, related not only to the occurrences of hailstorms, but to their related variables--hailstone size, accumulation of hailstones on the ground, duration of hailstorms--as well. Monthly issues of the U. S. Government publication "Storm Data" (1966-73) served as supplementary source material (U. S. Department of Commerce, 1940-73).

Information relating to rainfall within the High Plains area was derived from the Department of Commerce monthly publications, "Climatological Data for Texas" and "Local Climatological Data." The monthly editions of "Climatological Data for Texas" provided daily rainfall data for every observation station in the 14-county area. These data, vital to the study, gave indications of the changes in the rainfall distribution in the High Plains during the period under examination. Of the 22 stations in the 14-county region measuring rainfall, only six of them failed to report 100% of the time. The unavailable data were few and could not have affected significantly the results of the analysis. "Local Climatological Data" publications were available for Lubbock city only, a reporting station of the National Weather Service, but did provide the essential information for use in determining a workable definition of "storminess."

The rainfall and hailstorm data used in the analysis span the period 1966-73, the latter four years being the time when seeding of clouds was performed in Hale, Lamb, and Floyd counties. No cloud seeding was initiated during the first four years of the period. Only the months May through October were considered in the study as cloud seeding was not attempted at any other time during a given year. Additional rainfall data spanning the period 1940-65 for Plainview, Lubbock, and Brownfield were obtained.

Hail data were obtained for all fourteen counties under investigation: Bailey, Briscoe, Castro, Cochran, Crosby, Floyd, Hale, Hockley, Lamb, Lubbock, Lynn, Parmer, Swisher, and Terry. The data provided information on the following variables relating to hailstorm occurrence: average and maximum size of hailstones, the average and maximum depth of accumulation of hailstones on the ground, and the duration of the hailstorms. These data were then prepared in coded form on cards for computer processing.

Daily rainfall data were available for 22 observation points within the area of the High Plains under study (Fig. 1). The counties and their respective stations are listed below:

County	Stations		
Floyd	(1) Floydada	(2) Floydada 9 SE	
Hale	(1) Abernathy	(2) Plainview	
Lamb	(1) Littlefield	(2) Olton	
Bailey	(1) Muleshoe		
Briscoe	(1) Quitaque	(2) Silverton	
Castro	(1) Dimmitt 6 E	(2) Dimmitt	(3) Hart
Cochran	(1) Morton		
Crosby	(1) Crosbyton	(2) Lorenzo	
Hockley	(1) Levelland		
Lubbock	(1) Lubbock		
Lynn	(1) Slaton 5 SE	(2) Tahoka	
Parmer	(1) Friona		
Swisher	(1) Tulia		
Terry	(1) Brownfield		

These 24-hr rainfall amounts, with the monthly precipitation totals, were encoded on cards for use by the computer.

B. AGRICULTURAL DATA

Agricultural data used in this analysis are directed toward the establishment of the effectiveness of the hail suppression activities. Primary data critical to the economic evaluation aspects of the study are producer records of the U. S. Department of Agriculture and the Agricultural Stabilization and Conservation Service (USDA, ASCS). Other hail damage data collected include statistics of the Federal Crop Insurance Corporation, and the Crop-Hail Actuarial Association. In all cases, the hail damage data are for cotton production. Data were obtained from the Federal Crop Insurance Corporation for 1956-73, for the Crop-Hail Actuarial Association for 1967-73, and for producers for 1971-73.

The data collected from each source are:

1) Crop-Hail Actuarial Association by county and year
    - a. Liability (insurance coverage in dollars)
    - b. Premiums
    - c. Losses

2) Federal Crop Insurance Corporation by county and year
    - a. Liability
    - b. Premiums
    - c. All losses

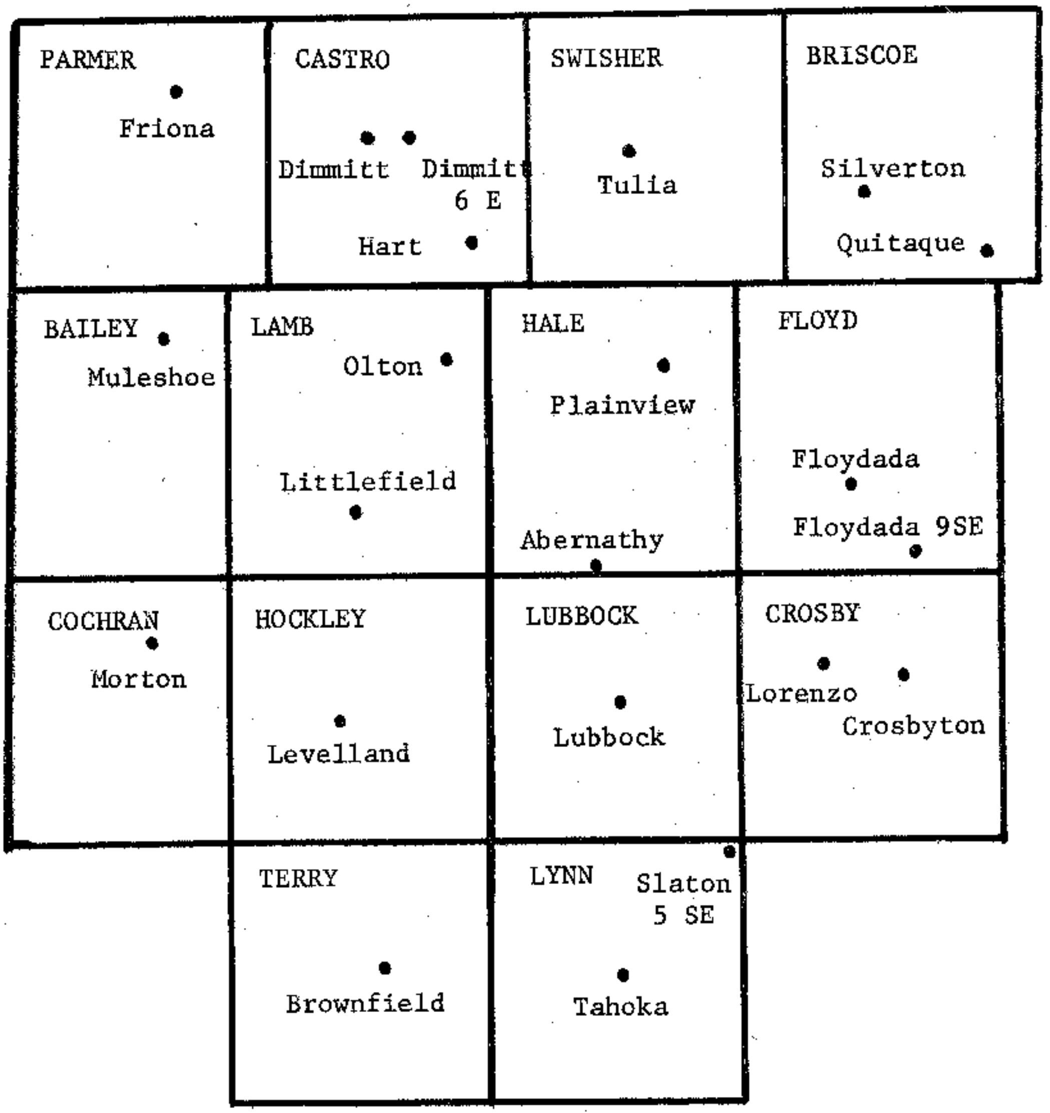

PARMER
Friona
CASTRO
Dimmitt
Dimmitt 6 E
Hart
SWISHER
Tulia
BRISCOE
Silverton
Quitaque
BAILEY
Muleshoe
LAMB
Olton
Littlefield
HALE
Plainview
Abernathy
FLOYD
Floydada
Floydada 9SE
COCHRAN
Morton
HOCKLEY
Levelland
LUBBOCK
Lubbock
CROSBY
Lorenzo
Crosbyton
TERRY
Brownfield
LYNN
Slaton 5 SE
Tahoka

Fig. 1. Locations of regular and cooperative observing stations of the National Weather Service within the 14-county area under study.

   d. Acres insured
   e. Losses by category (drought, hail, excess moisture, freeze, flood, wind, insects, disease, and all other)

3) USDA producer records by field within county by year and for cotton

   a. Acres affected
   b. Total acres
   c. Actual yield each year
   d. Adjusted yield as approved by ASCS committee
   e. Adjusted 3-yr average yield
   f. Reason for a yield loss (hail, freeze, wind, drought, other)

The data provided by the Crop-Hail Actuarial Association does not include acres insured or quantity of crops lost. This means an estimate of yield loss due to hail cannot be developed. This severely limits the usefulness of these data in developing estimates of the effect of hail suppression activities on hail damages. The data, however, provide general information on the magnitude of hail loss as a per cent of total liability.

The Federal Crop Insurance data include sufficient detail to develop pounds of cotton lint lost to hail per insured acre. Other estimates that have been calculated from these data are hail indemnity as a per cent of total liability and total indemnities for all causes as a per cent of total liability.

Producer records from county offices of the USDA, ASCS on weather-related yield losses for the study area were completed in late October. These data were collected for 12 counties and include approximately 14,000 observations. These records included an estimate of weather-related losses but indicated only the magnitude of the loss and enumerated the factor(s) responsible. When several weather factors were responsible for a yield loss, estimates of the amount of loss attributable to each factor was not available.

CHAPTER III. METHODOLOGY OF STATISTICAL ANALYSIS

A. GENERAL

It is the objective of the data analysis to estimate the effect (if any) of cloud seeding on:

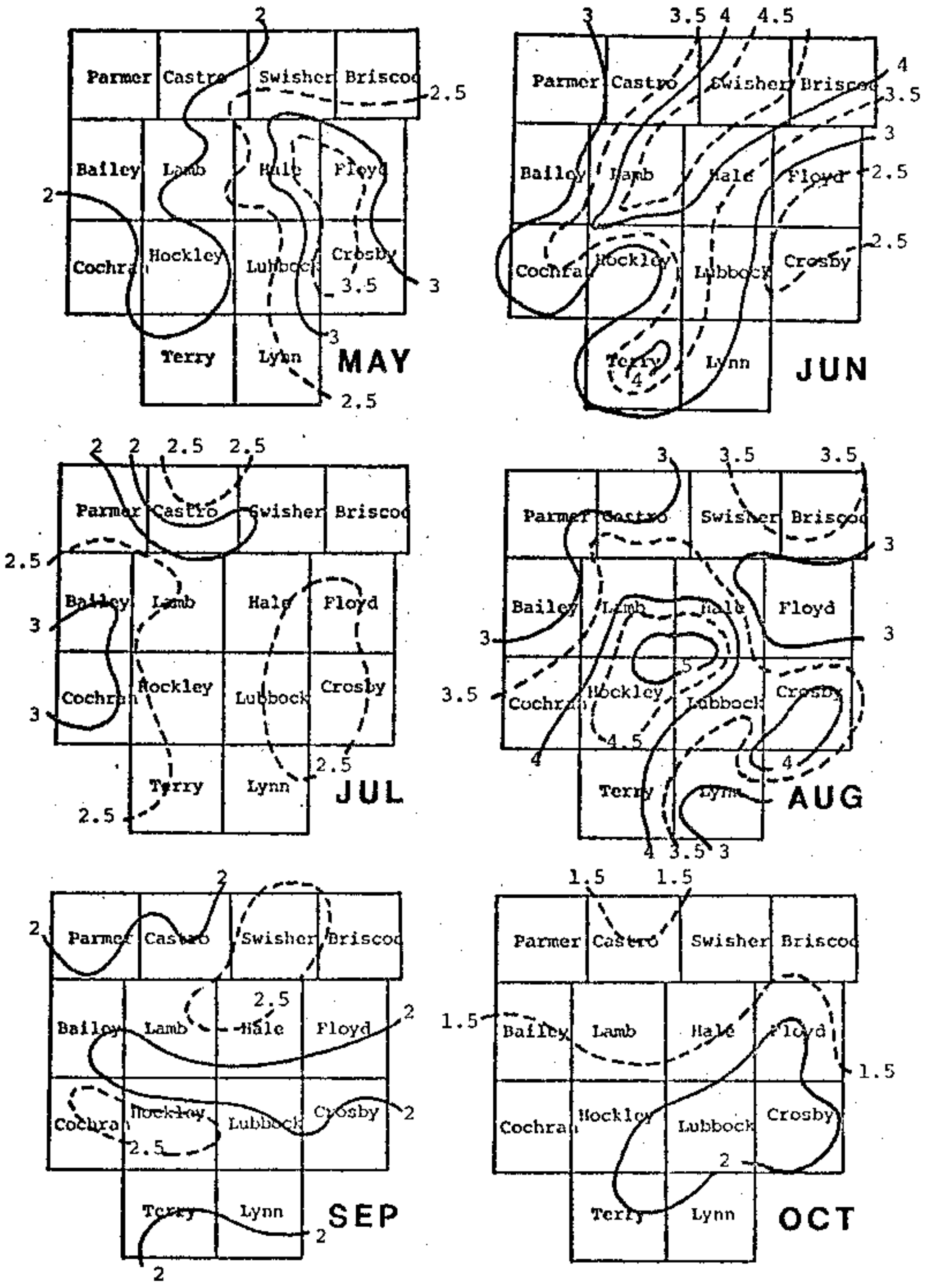
(1) rainfall during the agricultural season May through October, and
(2) hailstorm occurrences during the same period.

In order to achieve this objective we must, as far as possible, avoid fallacious inferences which ascribe to cloud seeding an observed effect on rainfall and/or hail which, in reality, is due to other causes. To illustrate such fallacies let us assume that we were to compare the rainfall in a particular county recorded during the years when cloud seeding occurred with this county's rainfall in the years preceding the cloud seeding, then the observed difference may simply be due to the fact that the rainfall in the South Plains region, in general, was higher (or lower) during the years when seeding occurred compared to the years preceding seeding, irrespective of the seeding operations. Likewise, if the rainfall in the cloud-seeded counties is compared with that of the non-seeded (control) counties in the same year, any observed difference in rainfall may be due to persistent differences in the precipitation levels observed in the two sets of counties during the year. Similar considerations apply to hail storms. The statistical analysis has the objective to eliminate such biases from the estimates of the effect of cloud seeding. The technique used to achieve this aim is the 'analysis of variance' and the specific type of analysis employed for the rainfall and hail data are described in Sections B2 and B3 below. A graphical analysis which in its essential concepts is equivalent to the analysis of variance is presented in Section B1.

B. ANALYSIS OF RAINFALL DATA

1. Graphical

Daily and monthly rainfall data have been presented in three sets of maps for the area of the South Plains under study. First a set of maps was adapted to depict the distribution of monthly rainfall over the 14-county region (Appendix B). Maps for each month, May through October, for each of the eight years (1966-73) gave the measured rainfall totals at each observing point in the region. Isohyets are drawn on each of the maps to show points having equal amounts of rainfall. A second series of maps shows the county average rainfall distribution in the study area (Appendix C). An average value is calculated for each county by summing the monthly totals for each reporting station in the given county, then averaging to get one representative value. Again, maps for each month, May through October, for each of the eight years are given. A third set compares those years of cloud seeding and those when no modification was attempted (Figs. 2-5).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Lubbock
Crosby
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Fig. 2 Patterns of observed average monthly rainfall (in.), 1966-69.

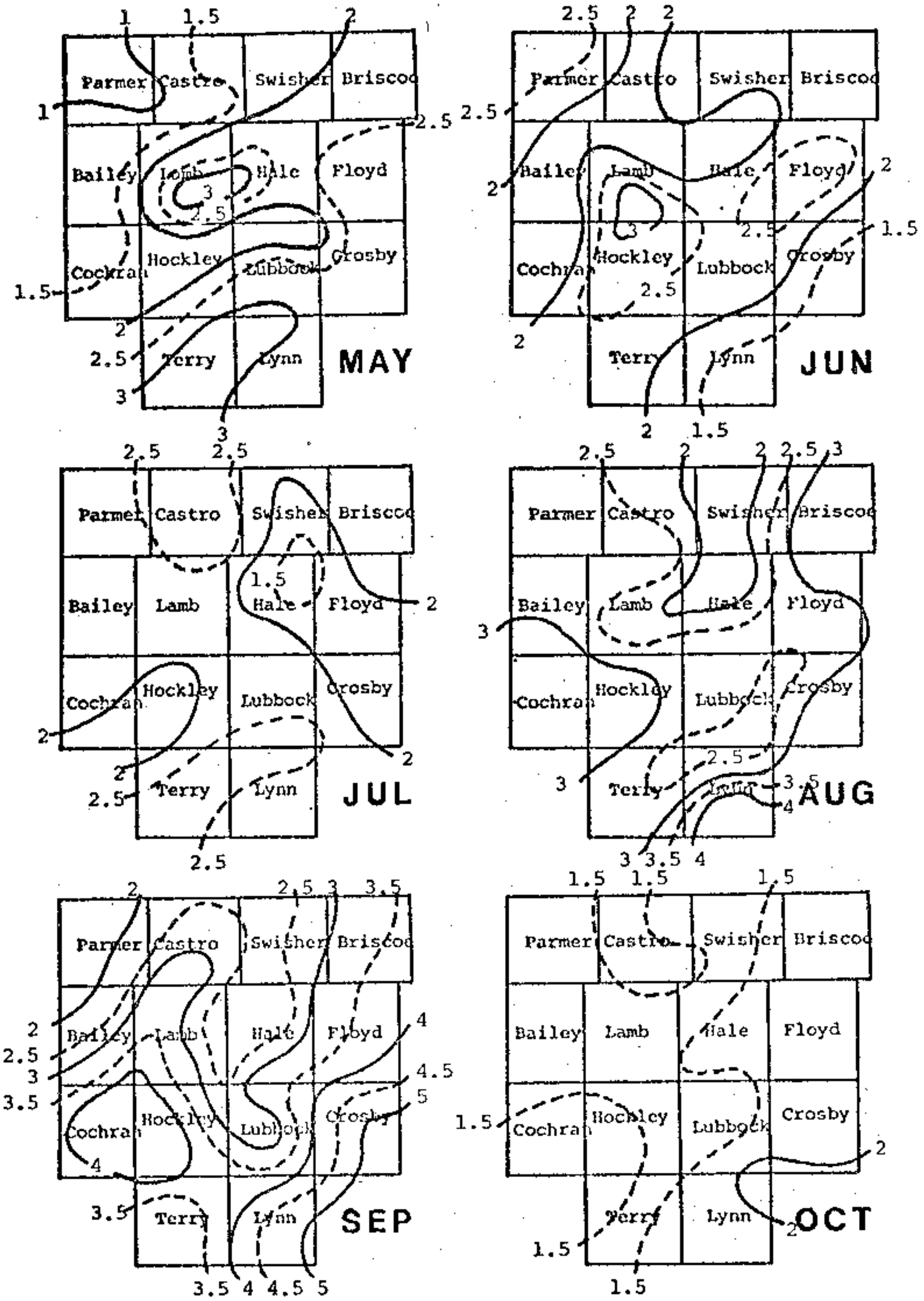
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Fig. 3 Patterns of observed average monthly rainfall (in.), 1970-73.

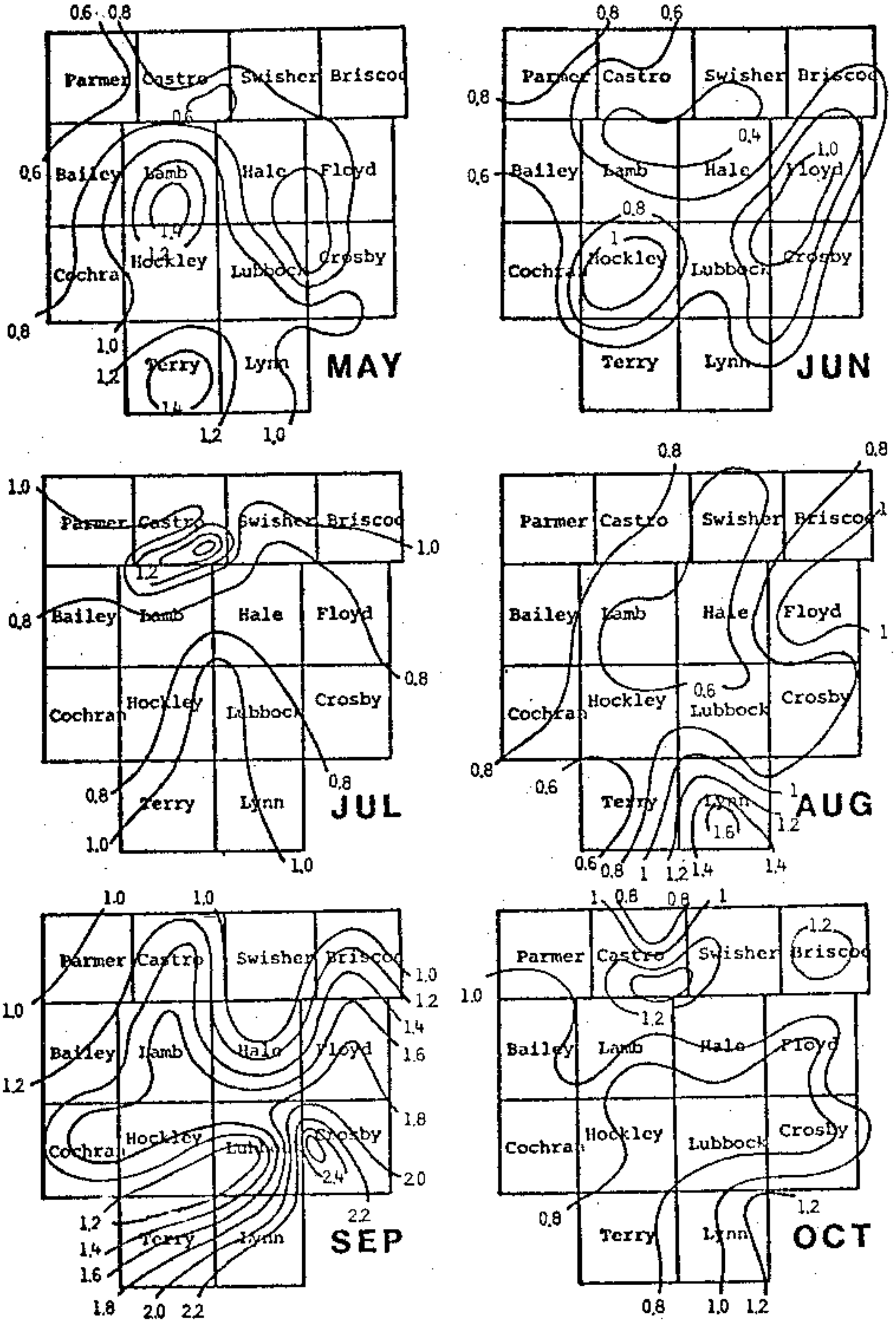
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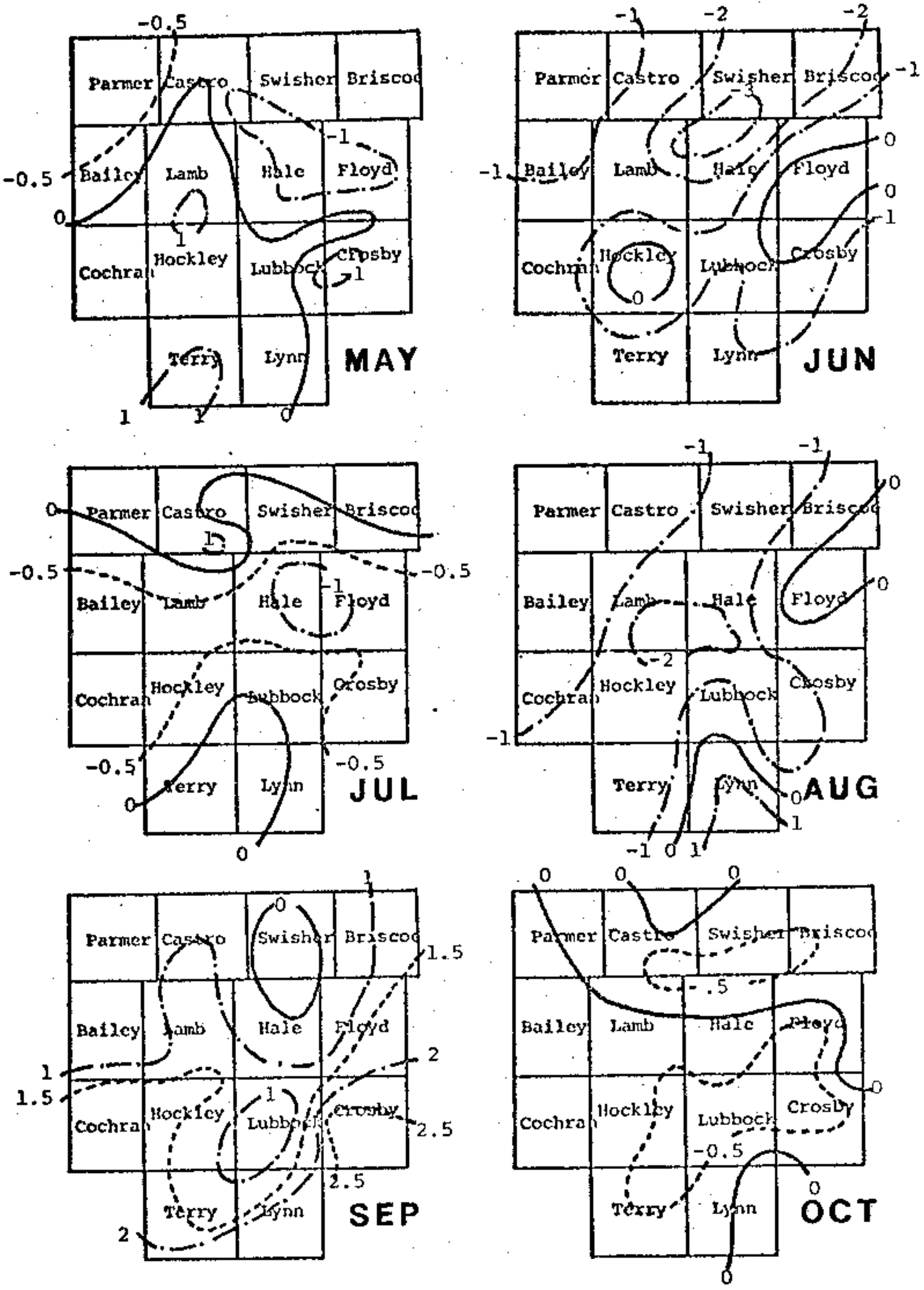
Fig. 4 Patterns of the ratio of the mean monthly rainfall of 1970-73 to the mean monthly rainfall of 1966-69.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0
1
SEP
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1
1.5
2
2.5
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.5
-0.5

Fig. 5 Patterns of the observed difference between the mean monthly rainfall of 1970-73 and the mean monthly rainfall of 1966-69.

The maps of average monthly precipitation for the two periods, 1966-69 and 1970-73, serve to present a smooth version of the rainfall distribution for the respective periods (Figs. 2 and 3). An additional map reveals the ratio of the average rainfall during the earlier 4-yr period versus that of the latter period (Fig. 4). Finally the graphical subtraction of the average rainfall for the 1966-69 period from the 1970-73 interval shows the trend in rainfall for each of the months May through October (Fig. 5).

The series of maps indicating the ratio of the average rainfall during the seeding period versus that of the preceding four years are used to ascertain the areal percentage change in rainfall over the study period (Fig. 4). Graphical interpolation techniques were utilized to find the fraction of land area within each county having various percentage changes during the seeded period compared with the non-seeded period. The methods described here use rather subjective approaches but the techniques used in the following discussion utilizes a more objective procedure. The graphical data presented here will be interpreted in a subsequent section.

2. Analysis of Variance*

The data entered into the analysis are the monthly rainfall records of 6 months in each of 8 years at each of 22 stations, i.e., a total of 1056 records. The analysis of variance now decomposes the total variation in the rainfall data into the following components ascribable to specified 'Sources of Variations' as shown on the following page.

NAME OF SOURCE	DESCRIPTION OF SOURCE OF VARIATION
(a) Between years	Systematic differences between the average rainfall for the 8 years averaged over the 6 months in the 22 stations.
(b) Between months	Systematic differences between the monthly rainfall averaged over all years and all stations.
(c) Between stations	Systematic differences between the rainfall records of the 22 stations averaged over the 8 years and 6 months.

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*For a quantitative description of the well-known statistical technique of 'analysis of variance' see the textbook by B. Ostle (1963) for the basic concepts of 'sources of variation' and the analytic and numerical techniques of an analysis of variance of 'balanced data'. In the present case we are faced with performing an analysis of variance for 'unbalanced data'. The technique here applicable is described in the textbook Draper and Smith (1966) (Chapter 9 pages 243-262).

(d) Interaction between months and years	Differences between the monthly rainfall patterns from year-to-year (averaged over all stations). In other words this component of variation is large if there are quite different monthly rainfall patterns in the 8 years.
(e) Contrast due to cloud seeding	The contrast of the 1970-73 rainfall records at the stations in Hale, Lamb, and Floyd counties versus the remaining rainfall but eliminating from this contrast any variations that are ascribable to the other sources (a) to (d).
(f) Residual	The remaining component of the total variation not ascribable to sources (a) to (e) and used as experimental error.

The statistical test which would indicate an effect of seeding on rainfall would then compare the seeding component (e) with the experimental error (f).

For the benefit of the reader versed in statistical concepts the above analysis of variance is based on the following model (Ostle, 1963).

$$y_{tms} = \alpha + \Sigma_t \beta_t x_t + \Sigma_m \gamma_m z_m + \Sigma_{mt} \delta_{mt} u_{mt} + \Sigma_s \zeta_s v_s + \omega w_{ts} + e_{tms} \qquad (2)$$

where

y_{tms} = total rainfall at station s in the month m of year t

$t=1...8; m=1...,6; s=1,...22.$

$x_t = x'_t - x'_8$ for $t=1,...,7$ and

$$x'_t = \begin{cases} 1 & \text{for all records in year } t \\ 0 & \text{for all records not in year } t \end{cases}$$

$z_m = z'_m - z_6$ for $m=1,...,5$ and

$$z'_m = \begin{cases} 1 & \text{for all records in month } m \\ 0 & \text{for all records not in month } m \end{cases}$$

$u_{mt} = x_t z_m$ for $t=1,...,7;\; m=1,...,5$

$v_s = v'_s - v'_{22}$ for $s=1,...,21$ and

$$v'_s = \begin{cases} 1 & \text{for all records from station } s \\ 0 & \text{for all records not from station } s \end{cases}$$

$$w_{ts} = \begin{cases} 1 & \text{for all records of the stations } s \text{ in cloud seeded counties during years of cloud seeding operations} \\ 0 & \text{for all other records} \end{cases}$$

3. X^2 Goodness-of-Fit Tests

Whereas the analysis of variance tests must be regarded as the most efficient tests for detecting an effect on the mean value of rainfall due to seeding, it is of some interest to investigate the possibility that seeding may have an effect on the distribution (sometimes represented in the form of a statistical histogram) of rainfall data.
For example, it may be that seeding would be effective in avoiding months of very low rainfall. The criterion for comparing two frequency distributions is the so-called Chi Square (X^2) (see e.g., Ostle (1963) Ch. 11, 12, and 13). The frequency distribution for each month was computed by using the observed occurrences per class interval of the amount of rainfall. The X^2 tests were then employed for the comparison of the frequency distribution of the seeded counties during the seeded period with those not seeded during the same period.

C. ANALYSIS OF HAIL DATA

In this report the analysis of the hail data consists of the following aspects, viz.,

(1) summary tabulations for Crop-Hail Actuarial Statistics,
(2) summary tabulations of Federal Crop Insurance Corporation Statistics,
(3) summary tabulations of U. S. Department of Agriculture Records (ASCS),
(4) statistical analysis of the data under (3),
(5) statistical analysis of the data under (2), and
(6) statistical analysis of some measures of hail intensity from data supplied by the State Climatologist's Office.

The results of these analyses are given later. The first three are self-explanatory. We confine ourselves here to a description of the methodology for (4), (5), and (6).

We first turn to a statistical analysis of the hail data of the cotton crop losses due to hail as reported to the ASCS County Offices and we are, therefore, making our assessment by a comparison of cotton operators in the hail suppression program counties with those in nine control counties in the same years.

The present analysis will proceed in two stages, viz,

(1) it will estimate the effect of cloud seeding on the percentage loss of cotton incurred by operators who report losses due to hail damage, and

(2) it will estimate the effect of cloud seeding on the percentage of cotton operators reporting any cotton losses due to hail.

We now turn to an outline of the detailed methodology under these stages. The main measure of hail incidence used in this analysis is the ratio

$$\text{lbs of cotton lost/expected total cotton harvest.} \qquad (3)$$

Unfortunately the numerator of this ratio represents the total pounds of cotton lost due to hail. Therefore, it represents pounds of cotton lost through hail damage only for those operators who report hail damage as the only cause of their cotton losses. For operators who report causes of cotton loss due to multiple causes other than hail, their reports only give their total pounds of cotton lost due to all causes. In addition the reports indicate which of the following causes of loss in addition to hail were operative: drouth, wind, freeze, rain, cold, or other.

Our analysis, therefore, adjusts the total percentage losses for losses through the above causes and enters a ratio lbs cotton lost due to hail/expected total cotton harvested (4)

into the remainder of the analysis of variance which represents a decomposition of the total variation in (4) into components ascribable to sources of variation as shown below:

SOURCE OF VARIATION	DESCRIPTION OF SOURCE OF VARIATION
(a) Between years	Systematic differences in the average percentage hail losses from year-to-year.
(b) Between counties within county groups	Differences between average percentage hail losses suffered by operators in different cloud-seeded counties and in 'different control counties' averaged over years.
(c) Interaction of counties by years within county groups	Variation of the county differences under (b) from year-to-year. This component serves as the valid experimental error.
(d) Cloud seeding contrast	Differences between the percentage hail losses of operators in Hale, Lamb, and Floyd counties as compared with those in the remaining counties but eliminating from this contrast any variation ascribable to sources (a), (b), and (c).
(e) Residual	The remaining component of the total variation not ascribable to sources (a) to (d).

Contrast (d) represents our estimate of the effect of cloud seeding on the average percent loss of cotton due to hail. This contrast must be compared with the component (c) interaction of counties by years within county groups. The reason for this is that the loss measure (3) for operators in the same county are highly correlated because normally a hail storm will simultaneously afflict neighboring operators in the same county, thereby fallaciously generating an abundance of loss measures which are not independent. On the other hand, the interaction component (c) regards the loss measure for a county in a year as a single observation of a percentage loss.

For the benefit of the reader versed in statistical concepts the above analysis of variance is based on the following model:

$$P_{tco} = \alpha + \Sigma_t \beta_t x_t + \Sigma_c \gamma_c z_c + \Sigma_c \delta_c u_c + \omega w_{tco} + \Sigma_{ct} d_{ct} v_{tc} + e_{tco} \qquad (5)$$

where $x_t = x_t' - x_3'$ for t=1, 2 and

$$x_t' = \begin{cases} 1 & \text{for all records of year } t \\ 0 & \text{for all records not of year } t \end{cases}$$

$$z_c = z_c' - z_3' \qquad c=1,\ 2$$

$$z_c' = \begin{cases} 1 & \text{if record is from seed county } c \\ 0 & \text{if record is not from seed county } c \end{cases}$$

$$u_c = u_c' - u_{14}' \qquad c=4,\ldots,13$$

$$u_c' = \begin{cases} 1 & \text{if record is from control county } c \\ 0 & \text{if record is not from control county } c \end{cases}$$

$$v_{tc} = \begin{cases} x_t z_c & \text{for } c=1,2 \\ x_t u_c & \text{for } c=4,\ldots,13 \end{cases}$$

$$w_{tco} = \begin{cases} 1 & \text{if record is from counties } c=1,\ 2,\ 3 \\ 0 & \text{if record is from counties } c=4,\ldots,14 \end{cases}$$

P_{tco} = lbs cotton lost due to hail/expected total cotton harvested by operator o of county c in year t. Actually P_{tco} is computed from the ratio lbs cotton lost from all causes/expected total cotton harvested but adjusted for losses due to other causes.

It should be noted carefully that the above analysis examined the possible effect of cloud seeding on the average cotton loss due to hail reported by operators who suffered hail damage. It is, however, quite conceivable that cloud seeding may have an effect on the frequency with which operators report hail damage. It was, therefore, decided to adjoin to the above analysis a study of a possible effect of cloud seeding on the percentage of cotton operators reporting any cotton losses due to hail. These percentages were computed for twelve of the above fourteen counties, i.e., the cloud-seeded counties (Floyd, Hale, and Lamb) and nine of the control counties for the years 1970-73. Both the number of operators reporting hail damage (as well as the number of cotton operators in each county) was obtained from the USDA statistics. In order to assess whether there was a smaller percentage of cotton operators reporting hail damage in the cloud-seeded counties compared with the control counties, an analysis of variance was carried out to decompose the total variation in these percentages into components ascribable to sources of variation as shown below:

NAME OF SOURCE	DESCRIPTION OF SOURCE OF VARIATION
(a) Between years	Systematic differences between the average percentages of operators from year-to-year.
(b) Between counties within county groups	Differences between average percentage operators in different cloud-seeded counties and in different control counties averaged over years.
(c) Cloud seeding contrast	Differences between the percentage hail losses of operators in Hale, Lamb, and Floyd counties as compared with those in the remaining counties but eliminating from this contrast any variation ascribable to sources (a) and (b).
(d) Residual	The remaining component of total variation not ascribable to sources (a) to (c). This is in essence the interaction between (a) and (b) and is a valid experimental error.

For the benefit of the reader versed in statistical concepts, the above analysis of variance is based on the following model:

$$y_{tc} = \alpha + \Sigma_t \beta_t x_t + \Sigma_c \gamma_c z_c + \Sigma_c \delta_c u_c + \omega w_{tc} + e_{tc} \tag{6}$$

where y_{tc} is the arcsin transformation of the percentage operators in county c and year t, where $x_t = x'_t - x'_3$ for t=1, 2, and

$$x'_t = \begin{cases} 1 & \text{for all records of year } t \\ 0 & \text{for all records not of year } t \end{cases}$$

$z_c = z'_c - z'_3$; c=1, 2

$$z'_c = \begin{cases} 1 & \text{if record is from seed county } c \\ 0 & \text{if record is not from seed county } c \end{cases}$$

$u_c = u'_c - u'_{12}$ c=4,...,12

$$u'_c = \begin{cases} 1 & \text{if record is from control county } c \\ 0 & \text{if record is not from control county } c \end{cases}$$

$$w_{tc} = \begin{cases} 1 & \text{if record is from counties } c=1,2,3 \\ 0 & \text{if record is from counties } c=4,\ldots,12 \end{cases}$$

The analysis given in Chapter IV, Section B will combine the evidence contained in the analysis of average cotton loss due to hail with the evidence contained in the analysis of the percentage of operators reporting hail damage.

We next turn to the statistical analysis of the data from the Federal Crop Insurance Corporation. This corporation provides data by county and by year for pounds of cotton lint lost due to hail damage per acre insured. These data are summarized in Table 12 of Chapter IV. Since only annual data of cotton losses are given for each county, the statistical analysis (analogous to the one for the ASCS hail loss data) now only contains measurements of variation due to the sources of variation (a) to (d) and again the component (c) is used as a valid error for tests of significance.

We now turn to the analysis of data of hail damage provided by the State Climatologist's Office. These data represent various measures of hail intensity of individual storms. Measurements taken include the duration of the storm; maximum, average, and ranges of hailstone diameters; and averages and ranges of hailstone depth or accumulation. The data for these measures are, however, far from uniform over the various reporting stations. Thus, for example, some stations report only average hail sizes while some report maxima or ranges, etc. The most complete data are available on average hailstone sizes.

For a limited number of observations, both maximum and average diameters were given. For these data a logarithmic-linear regression model was estimated to relate average to maximum diameter. This regression was used to estimate average diameter of hail sizes for storms in which only maxima were given.

These data comprise some 54 observations on average hailstone diameters which were analyzed by a model very similar to that used for the ASCS data described above, viz, with sources of variation consisting of between years, between counties within county groups, cloud seeding contrast, and residual.

CHAPTER IV. RESULTS OF THE ANALYSIS

A. ANALYSIS OF RAINFALL DATA

1. Graphical

a. The long-range trend in rainfall. Whenever monthly and annual rainfall totals are plotted, certain identifiable trends are depicted by the variations in measured rainfall from month-to-month and year-to-year. The sum of the monthly totals (May through October) of rainfall were plotted for Brownfield, Lubbock, and Plainview (Fig. 6). These stations were selected randomly to provide a view of the trend in precipitation over an extended time period within and outside the seeded region. They were among seven observing stations for which data were available on a continuous basis for the period 1940-73.

The total rainfall for the 6-mo period for Brownfield (Fig. 6) was observed to fluctuate generally from six to 20 in. over the 34-yr period. Extreme maxima (30 in. or greater) occurred once in 30 yr. By contrast, rainfall totals of 8 in. or less occurred seven times during the same 30-yr period. The extremum present during the cloud seeding period was matched only once during the entire 34-yr term. During the 4-yr cloud-seeding period, the total rainfall was observed to fluctuate twice between eight and 30 in. The magnitude of this fluctuation was duplicated only once--at the time of occurrence of the other extremum.

Fluctuations in total rainfall at Lubbock were not as marked as those at Brownfield. Again, the seeded period was characterized by comparatively large fluctuations in total rainfall, although the extremum during the period was not as substantial as that at Brownfield. These fluctuations, the magnitude of which exceeded 10 in, were not uncommon, however, and occurred three times prior to the seeded period.

The outstanding feature of the plotted total rainfall at Plainview, a station within the target area, is the absence of a pronounced maximum during the seeded period. The trend during the seeded period is analogous to those trends of Brownfield and Lubbock for the same period, but the maximum is some 10 in. less than the maxima of Brownfield and Lubbock. However, this feature is not without precedence. During the period 1948-50, the two non-seeded stations experienced a marked increase in total rainfall, whereas the total rainfall at Plainview sustained a comparatively small increase of three in. Also, consideration of the degree of fluctuation during the early half of the seeded period indicates that the magnitude of change from maximum to minimum to maximum at Plainview was equal to or greater than that at the unseeded stations.

The total number of rain days for the interval May-October for the 34-yr period 1940-73 provides a view of how the frequency of rainfall occurrence fluctuated at each of the three stations (Fig. 7). In each instance, the frequency of occurrence was observed to fluctuate

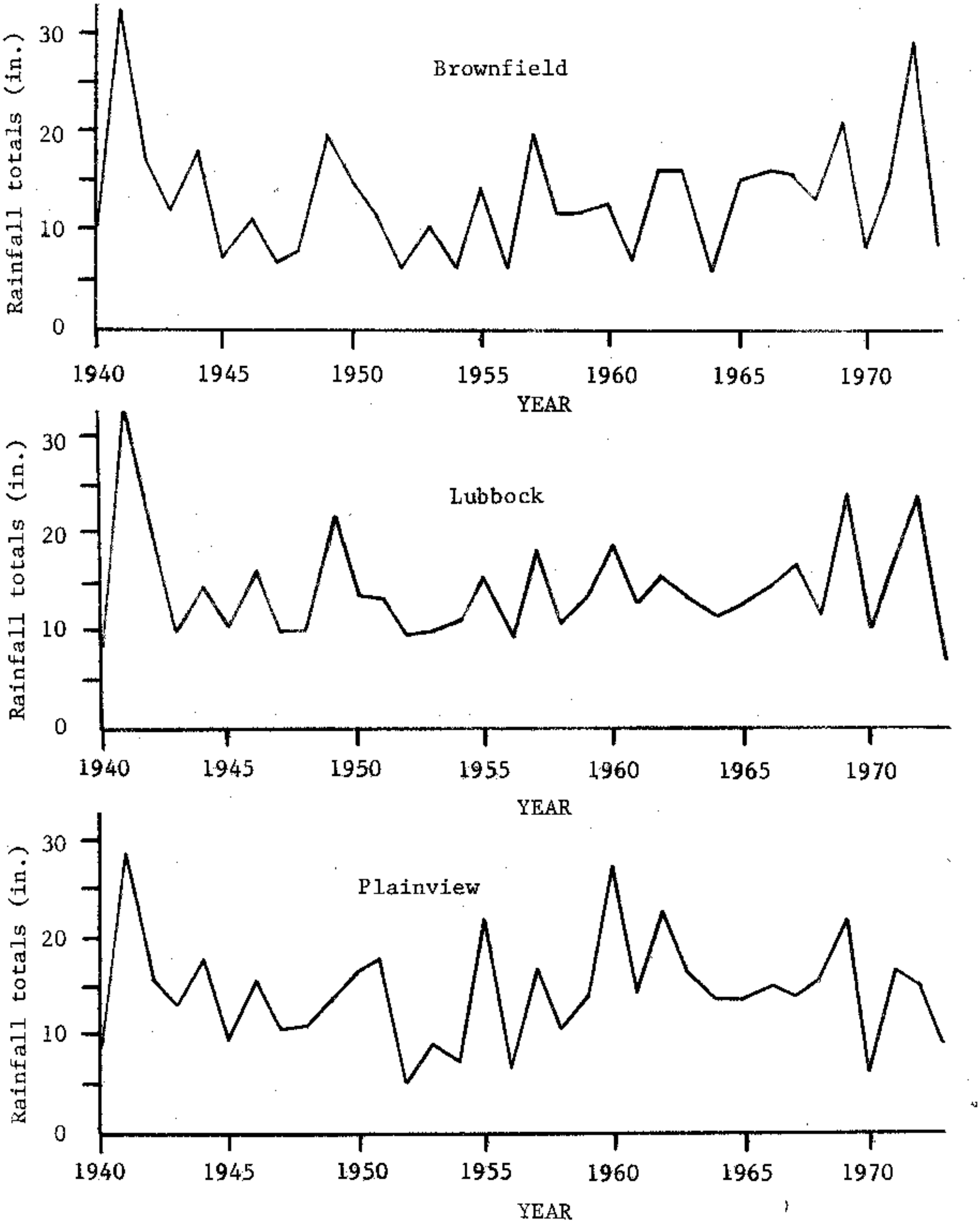


Fig. 6. Plot of the observed 6-month (May-October) rainfall totals for the period 1940-73.

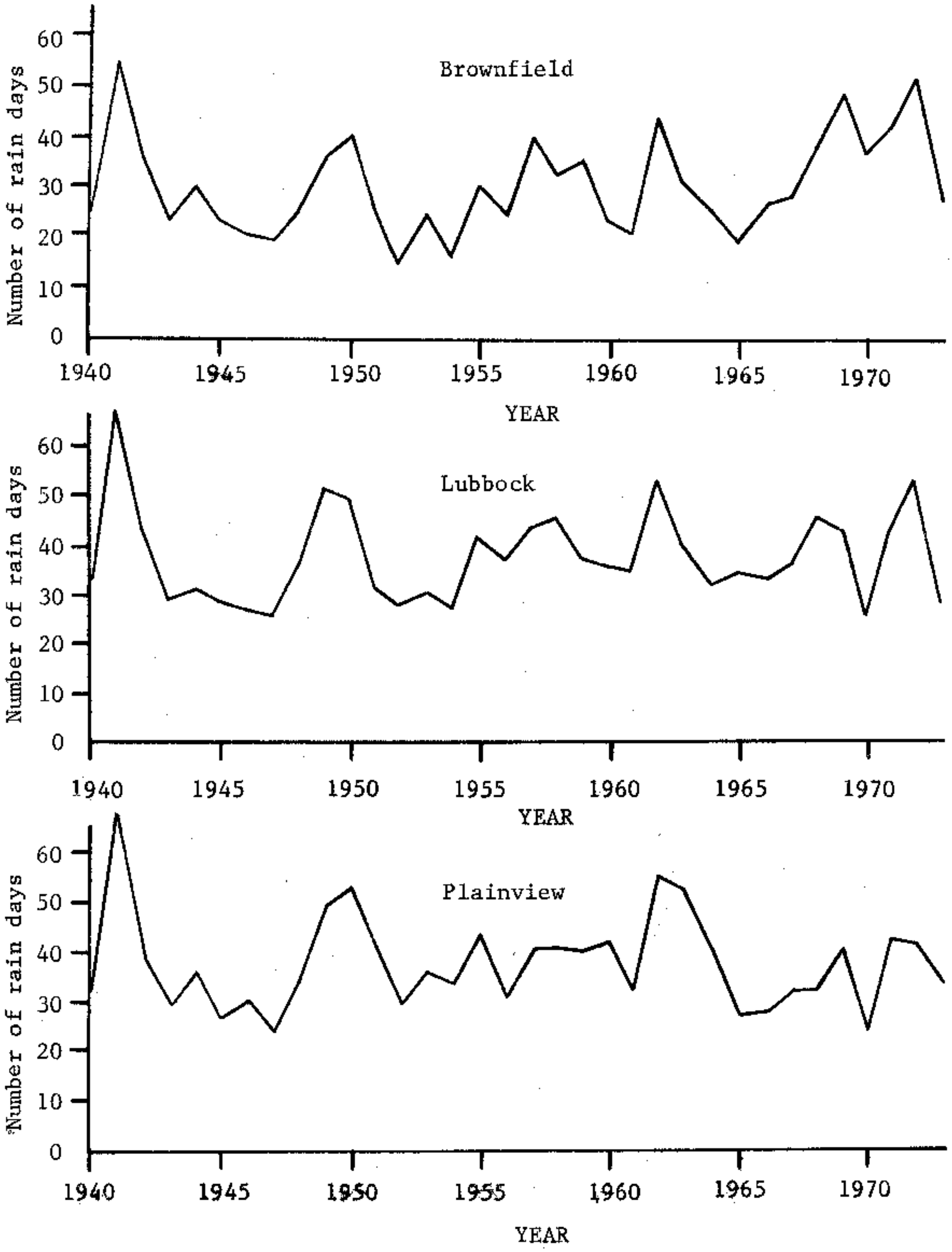


Fig. 7. Plot of the observed 6-month (May-October) totals of number of rain days for the period 1940-73.

much of the time coincidentally with the intensity of rainfall occurrence shown in Fig. 6. The greatest number of rain days at Brownfield, Lubbock, and Plainview occurred in 1941, with secondary maxima appearing regularly at all three stations later in the period. As with the rainfall totals considered above, the number of rain days reached a pronounced maximum at Brownfield and Lubbock, but not at Plainview, during the seeded period. By contrast, the decline in the number of rain days at Brownfield and Lubbock from 1972 to 1973 was more than three times as large as that at Plainview for the same years. The paucity of rain days at Plainview in 1970 was not a rare circumstance; on two other occasions, minima of that magnitude occurred.

When both the intensity and frequency of rainfall occurrence over a period of 34 years are examined at each of the three stations, it is seen that any minimum or maximum value, or any marked change from one year to the next, associated with the seeding period, has occurred at least once in the 30 years preceding the 4-yr seeding period. This suggests that such extremes may have occurred, and may occurr again regardless of the presence of cloud seeding efforts.

If it can be ascertained that the rainfall and rain-day data fit a normal distribution, then monthly and annual probability levels may be computed that would indicate the "probable" patterns of rainfall and rain-day occurrences in the target region were cloud seeding not introduced. If the data follow a normal distribution, then any differences between the expected and actual rainfall and rain-day patterns may be examined to determine the effects of cloud seeding on those patterns. As before, data from the three randomly selected stations were examined for normality by means of the Cornu, skewness, and Chauvenet tests (see Appendix D for a description of the normality tests). Computed statistical characteristics used in the normality tests, along with the results of the significance tests, are tabulated in Table 1 for Brownfield, Table 2 for Lubbock, and Table 3 for Plainview.

The Brownfield results show that the rainfall data for all months except July failed either the Cornu or skewness tests. The total rainfall for the 6-month period failed the skewness test. Only two months passed the Chauvenet test, while one other was borderline, denoted by (B). All five cases of failure were on the positive side of the frequency distribution. In every instance the extreme value was abnormally high. On the other hand, analysis of the rain-day data indicates that all periods but two passed both the Cornu and skewness tests. Of those periods that passed, two failed the Chauvenet test; when the extreme values were removed from the analysis, the data did not exceed the Chauvenet criterion. These results suggest that the assumption of normality of rainfall data is invalid in every month except July. Rain-day data appear to fit a normal distribution much more frequently than rainfall data for Brownfield.

For Lubbock, another observation point outside the seeded region, results indicate a normal distribution of rainfall only during the month of July. When the extreme datum is removed in an analysis of rainfall

Table 1. Computed monthly statistics and results of the normality tests on rainfall and rain-day data for Brownfield (N=34).

	Rainfall							Rain Days						
	May	Jun	Jul	Aug	Sep	Oct	Total	May	Jun	Jul	Aug	Sep	Oct	Total
Mean	2.59	2.44	2.41	1.93	2.25	1.96	13.58	5.53	5.26	5.94	4.68	5.03	4.47	30.91
Stn.dev.	2.51	1.83	1.73	2.00	2.02	1.94	6.20	2.55	2.70	3.41	3.34	2.99	3.30	10.17
S.E. mean	0.43	0.31	0.30	0.34	0.35	0.33	1.06	0.44	0.46	0.58	0.57	0.51	0.57	1.74
Maximum	13.11	9.61	5.52	9.29	7.26	6.67	32.88	12	9	17	14	12	14	55
Minimum	0.29	0.36	0.00	0.00	0.04	0.00	5.85	2	1	0	0	1	0	15
Cornu value	0.64	0.74	0.83	0.74	0.82	0.78	0.75	0.83	0.86	0.74	0.78	0.86	0.76	0.81
Cornu limits	0.74 to 0.86 for all periods													
Cornu test (P or F)	F	P	P	P	P	P	P	P	P	P	P	P	P	P
Skewness t-value	5.94	4.30	0.32	3.96	2.25	2.68	2.72	1.23	-0.20	1.74	2.10	1.10	2.48	1.45
T-value from table	2.03 for all periods													
Skewness (P or F)	F	F	P	F	F	F	F	P	P	P	F	P	F	P
Chauvenet value	4.19	3.92	1.80	3.67	2.48	2.43	3.11	2.54	1.38	3.24	2.79	2.33	2.89	2.37
Chauvenet table value	2.45 for all periods													
Chauvenet (P or F)	F	F	P	F	F(B)	P	F	F(B)	P	F	F	P	F	P

Table 2. Computed monthly statistics and results of the normality tests on rainfall and rain-day data for Lubbock (N=34).

	Rainfall							Rain Days						
	May	Jun	Jul	Aug	Sep	Oct	Total	May	Jun	Jul	Aug	Sep	Oct	Total
Mean	3.02	2.75	2.24	1.98	2.22	1.97	14.19	7.21	6.79	6.74	5.91	5.65	5.32	37.62
Stn. dev.	2.55	1.95	1.48	1.83	1.97	1.96	5.48	2.98	2.78	3.51	2.93	3.11	3.22	9.49
S. E. mean	0.44	0.33	0.25	0.31	0.34	0.34	0.94	0.51	0.48	0.60	0.50	0.53	0.55	1.63
Maximum	12.69	7.95	5.37	8.85	7.61	7.76	32.71	14	12	15	14	12	16	68
Minimum	0.10	0.32	0.00	0.00	0.00	0.00	6.89	2	1	0	0	0	0	25
Cornu value	0.69	0.79	0.86	0.70	0.83	0.79	0.75	0.77	0.83	0.79	0.75	0.81	0.74	0.77
Cornu limits	0.74 to 0.86 for all periods													
Cornu test (P or F)	F	P	P	F	P	P	P	P	P	P	P	P	P	P
Skewness t-value	4.32	2.19	0.43	4.03	1.87	2.93	3.04	1.20	-0.25	0.51	1.46	0.61	2.05	2.48
T-value from table	2.03 for all periods													
Skewness (P or F)	F	F	P	F	P	F	F	P	P	P	P	P	F	F
Chauvenet value	3.79	2.67	2.11	3.75	2.74	2.95	3.38	2.28	1.87	2.35	2.76	2.04	3.32	3.20
Chauvenet table value	2.45 for all periods													
Chauvenet (P or F)	F	F	P	P	F	F	F	P	P	P	F	P	F	F

Table 3. Computed monthly statistics and results of the normality tests on rainfall and rain-day data for Plainview (N=34).

	Rainfall							Rain Days						
	May	Jun	Jul	Aug	Sep	Oct	Total	May	Jun	Jul	Aug	Sep	Oct	Total
Mean	3.13	2.86	2.58	1.89	2.18	1.82	14.45	7.56	6.94	6.74	6.47	5.68	4.79	38.18
Stn.dev.	2.39	1.84	2.34	1.32	1.65	1.71	5.60	3.07	2.94	2.98	3.15	3.30	3.10	9.56
S.E. mean	0.41	0.32	0.40	0.23	0.28	0.29	0.96	0.53	0.50	0.51	0.54	0.57	0.53	1.64
Maximum	11.11	7.07	11.74	6.19	5.50	6.35	28.72	15	14	15	13	14	13	68
Minimum	0.23	0.28	0.12	0.03	0.00	0.00	5.20	2	1	1	1	0	0	24
Cornu value	0.73	0.83	0.72	0.78	0.84	0.79	0.74	0.79	0.76	0.76	0.82	0.73	0.82	0.75
Cornu limits	0.74 to 0.86 for all periods													
Cornu test (P or F)	F	P	F	P	P	P	P	P	P	P	P	F	P	P
Skewness t-value	3.14	0.95	4.39	2.31	1.22	2.24	1.31	1.35	0.97	0.34	0.75	1.40	1.30	2.41
T-value from table	2.03 for all periods													
Skewness (P or F)	F	P	F	F	P	F	P	P	P	P	P	P	P	F
Chauvenet value	3.34	2.28	3.91	3.27	2.02	2.65	2.55	2.43	2.40	2.78	2.07	2.52	2.65	3.12
Chauvenet table value	2.45 for all periods													
Chauvenet (P or F)	F	P	F	F	P	F	F	P	P	F	P	F(B)	F	F

during September, that month too assumes a normal distribution. As with the Brownfield data, in every instance when the extreme data failed the Chauvenet test, the values of the extrema were abnormally high. In all but two months, a normal distribution of rain days was indicated. However, the sum of all monthly rain days failed both the skewness and Chauvenet tests. Analysis of the Lubbock data corroborates the findings of the Brownfield data analysis, i.e., monthly rainfall generally does not fit a normal distribution. Only during certain months do the rain-day data appear to approximate normality.

Rainfall data for Plainview passed all three normality tests only for June and September. The total monthly rainfall of the 6-month study period passed the Cornu and skewness tests but failed the Chauvenet test, even when the extremum was deleted. Rain-day data for much of the study did not fit a normal distribution; only the data for May, June, and August passed all the normality tests.

To summarize the results of the Brownfield, Lubbock, and Plainview normality tests, since 76 per cent of the tested rainfall values passed the skewness test while only 29 per cent passed the Cornu test, it may be concluded that, for all practical purposes, the frequency distributions of the monthly rainfall are significantly different from a normal distribution. The Chauvenet test for extreme data values failed more than 70 per cent of the time. Rain-day data passed the Cornu test in every instance but one, while 76 per cent of the rain-day data passed the skewness test. However, since the Chauvenet test was passed less than 50 per cent of the time, it cannot be concluded that the rain-day data fit a normal distribution. In every case where either the rainfall or rain-day data failed the Chauvenet test, the failure was a result of an abnormally high value. A study of the other four stations with 34 years of data reveals similar results. Rainfall data for Crosbyton, Dimmitt 6E, Muleshoe, and Tulia passed the Cornu test only 67 per cent of the time, the skewness test only 22 per cent of the time. The Chauvenet test was passed only 11 per cent of the time. As with the three stations considered earlier, rain-day data of the four supplementary stations come closer to fitting a normal distribution than do the rainfall data. However, since only 78 per cent of the rain-day data passed the Cornu test and only 67 per cent passed the skewness test, it is reaffirmed that neither the rainfall nor the rain-day data fit a normal distribution.

As a result of the findings of this analysis, apparent non-normality of both the rainfall and rain-day data prevents the computation of any reliable probability levels. Even though several marked climatological trends in rainfall over an extended period at a given station are evident, non-normality of the data suggests that the duration and extent of these "wet" and "dry" periods are difficult to predict with accuracy. From a long-range view of the climate over the period 1940-73, the variations from year-to-year can be regarded as a matter of chance--random fluctuations--though they may be superimposed upon a trend.

b. Graphical investigation of the general rainfall patterns. Close scrutiny of the average monthly precipitation over the fourteen counties during the period of cloud seeding reveals, 1) early in the cloud seeding season (*viz.*, May and June) the heaviest rainfall occurred, on the average, in the three-county target area (Fig. 3); and 2) later in the season, the target area received drier weather than that of the adjacent control counties. Precipitation maxima in the summer months lay to the north and south of the seeded counties.

On the other hand, an analysis of the average monthly rainfall distribution over the High Plains during the period 1966-69 indicates that the heaviest rainfall occurred in and very close to the target counties, not only in the earlier half of the season under consideration, but the latter half as well (Fig. 2). Maximum values tend to be one to one and one-half inches greater during the period 1966-69 than those of the later period (this does not necessarily imply that seeding was responsible for the difference).

By contrasting the average precipitation of the non-seeded period 1966-69 with that of the seeded period 1970-73 within the target area reveals, 1) much of the target area experienced less rainfall during the four years of cloud seeding for the months May through August (Fig. 5), and where areas of greater rainfall did exist, in the western and eastern sectors of the target area, the increase was only slight; and 2) later in the season (*viz.*, September and October) only a very slight increase in rainfall during the cloud seeding years over the 1966-69 period was detectable.

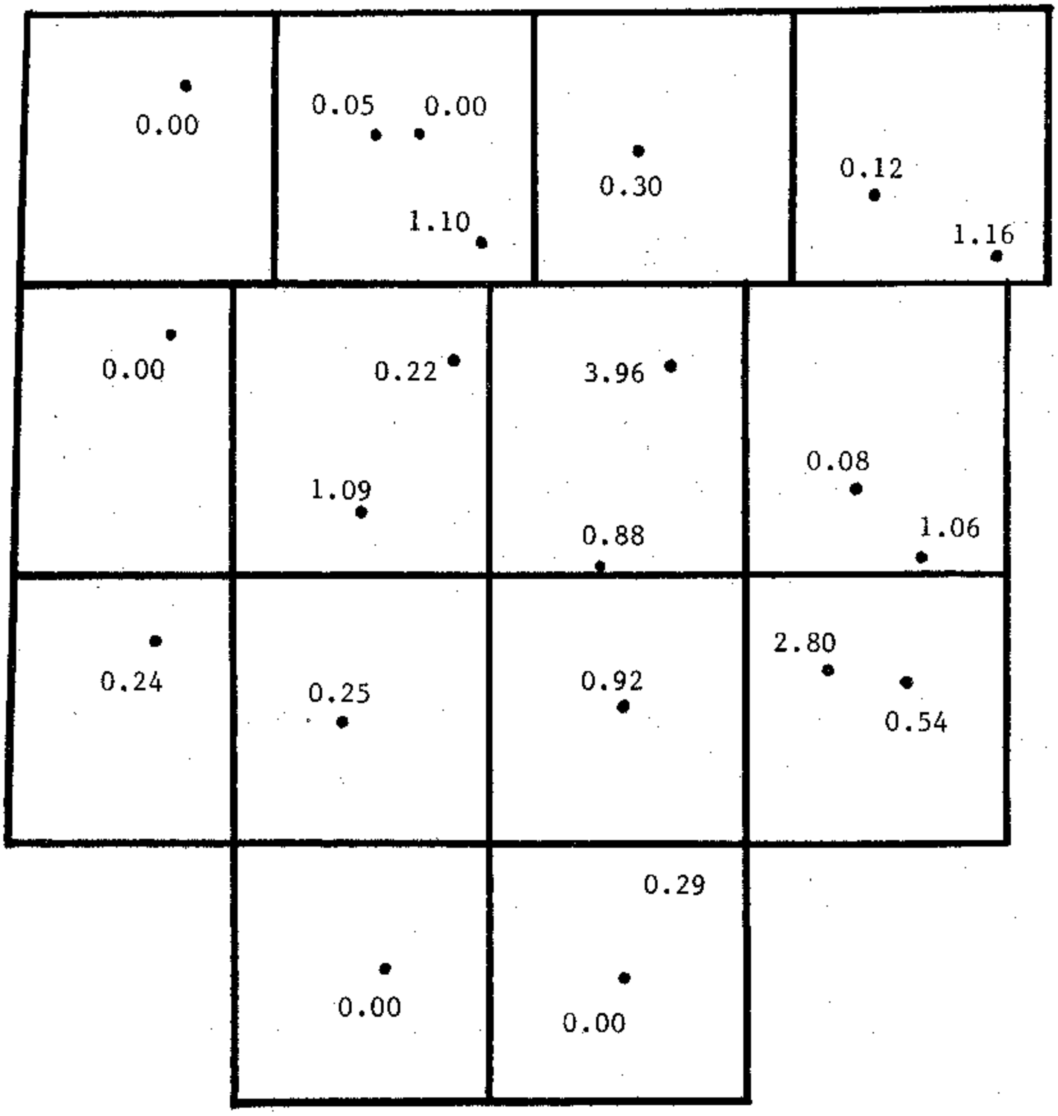
A comparison of the average rainfall of the two periods for the entire High Plains area discloses that the areal extent of rainfall increase during the years of cloud seeding is much greater in May and September than in any of the other four months (Fig. 4). Only small areas of rainfall increase characterized the hotter and drier summer months when convective activity is at a maximum. In almost every month an intrusion of relative rainfall increase appears along the southern boundary of the High Plains area. This feature may coincide with the presence of a prevailing southerly, moisture-laden wind over the area during the warm half of any year.

Several interesting features appear on the maps of normalized rainfall data (Appendix C). The driest weather during both seeded and non-seeded periods occurred upslope and upwind in the northwest quarter of the High Plains area under study. More often than not, the wettest section lay in the center of the 14-county area. The greatest range of rainfall amounts occurred most frequently in June and August of the period 1966-69, as demonstrated by the packing of isohyets on the maps. A common feature on the normalized rainfall maps is the intrusion of a "moist" or "wet" tongue into the study area from the south or southwest. This feature is particularly prominent during those years of cloud seeding activities. According to wind data available for Lubbock city, the prevailing wind direction over the area was, on the average, 173° (direction from which wind is blowing) during the years of cloud seeding, some 10° greater than the prevailing wind direction of the previous 4-year period.

One outstanding characteristic of the rainfall distribution typifying the Texas High Plains is the wide variation in measured rainfall over a relatively small land area. The rainfall totals of May 28, 1967 (Fig. 8) within the study area are an excellent and typical example of the extent to which rainfall amounts within individual counties may vary. Rainfall amounts varied nearly 4 in. within a distance of only 30 miles. Totals ranged from less than 0.1 in. to almost 4 inches in the target area alone. The extremely uneven distribution was evidenced by two stations measuring less than one-quarter inch, three other stations reporting around one inch of rain, and a sixth station recording a soaking one-day rain of nearly 4 inches.

c. Areal percentage changes in rainfall. Once the mean rainfall of both seeded (1970-73) and base periods (1966-69) were computed, an analysis of the areal distribution of rainfall over the study area could be made using ratios and graphical interpolation. Fig. 4 provides the indicated change in rainfall during the cloud seeding period as opposed to that of the base period for each of the 22 observing stations for each of the six months considered. Any value greater than one signifies that, at that station for that particular month, the average rainfall during the seeded period exceeded the average rainfall of the non-seeded period. Table 4 indicates, for each month, the type and degree of change in rainfall each county sustained between the two periods. Fig. 4 was utilized in preparing the tables.

An analysis of the areal distribution of rainfall over the study region during May (Table 4a) revealed that the difference between the mean percentage of the seeded and non-seeded counties was only 2%. Four of the 14 counties, including one of the three seeded counties, sustained an average increase in rainfall during the seeded period. In June (Table 4b), both the seeded and non-seeded counties experienced nearly identical percentage changes in rainfall. All but one county--Hockley--received, on the average, less rainfall in the seeded period compared with the base period. The difference between minimum and maximum percentage changes of the individual counties was somewhat less than that of May. Only in July and August (Tables 4c and 4d) did the change in rainfall of the target and control regions show any statistical difference. Yet, in August, the difference in percentage change in rainfall among the seeded counties themselves was greater than the difference between the three seeded counties and the 11 unseeded counties. In July, about half of the unseeded counties sustained an average increase during the seeded period as opposed to the unseeded period, while the percentage changes in rainfall of the three seeded counties were closely akin. The month of September (Table 4e) was unique, in that every county but one received, on the average, more rainfall during the seeded period than during the unseeded period. As with May and June, the percentage changes for both target and control areas for September were not statistically different. The same observation is valid for October as well (Table 4f), where the difference in percentage changes of the two sectors was only two percentage points.


0.00
0.05
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1.10
0.30
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1.16
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0.22
3.96
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0.08
1.06
0.24
0.25
0.92
2.80
0.54
0.29
0.00
0.00

Fig. 8. Observed 24-hr rainfall totals (in.) for 28 May 1967.

Table 4. Fraction (in tenths) of land area within a county having the indicated percentage change in rainfall during the cloud-seeded period, 1970-73, as compared with the rainfall measured during the base period, 1966-69, for each of the six months May through October (a through f).

a) MAY

Average Rainfall$_{(1970-73)}$ / Average Rainfall$_{(1966-69)}$

COUNTY	0-20%	21-40%	41-60%	61-80%	81-100%	101-120%	121-140%	141-160%	161-180%	181-200%	201%+	AVG %
Floyd			1	4	5							78
Hale			2	6	1	1						72
Lamb					2	3	3	2				120
Bailey			1	5	3	1						78
Briscoe					10							90
Castro			1	4	5							78
Cochran				2	7	1						88
Crosby			1	2	5	2						86
Hockley						8	2					114
Lubbock			1	2	2	5						92
Lynn					3	6	1					106
Parmer			7	3								56
Swisher				3	7							84
Terry						2	3	5				136

Mean percentage change of 3 seeded counties 90

Mean percentage change of 11 unseeded counties 92

b) JUNE

Average Rainfall$_{(1970-73)}$ / Average Rainfall$_{(1966-69)}$

COUNTY	0-20%	21-40%	41-60%	61-80%	81-100%	101-120%	121-140%	141-160%	161-180%	181-200%	201%+	AVG %
Floyd			1	2	4	3						88
Hale		2	4	3	1							56
Lamb		3	3	4								52
Bailey			2	8								66
Briscoe			6	4								58
Castro			7	3								56
Cochran			7	2	1							58
Crosby			4	2	3	1						72
Hockley				1	2	7						102
Lubbock			1	6	2	1						76
Lynn			8	2								54
Parmer			1	3	6							80
Swisher		2	8									46
Terry			7	3								56

Mean percentage change of 3 seeded counties 65

Mean percentage change of 11 unseeded counties 66

Table 4. (Continued)

c) JULY

Average Rainfall$_{(1970-73)}$ / Average Rainfall$_{(1966-69)}$

COUNTY	0-20%	21-40%	41-60%	61-80%	81-100%	101-120%	121-140%	141-160%	161-180%	181-200%	201%+	AVG %
Floyd				6	4							78
Hale				8	2							74
Lamb				5	3	1	1					86
Bailey				6	4							78
Briscoe					3	7						104
Castro					1	6	1	2				118
Cochran				10								70
Crosby				9	1							72
Hockley				4	3	3						88
Lubbock				1	6	3						94
Lynn					5	5						100
Parmer					5	5						100
Swisher				1	4	5						98
Terry				1	2	7						102

Mean percentage change of 3 seeded counties 79

Mean percentage change of 11 unseeded counties 93

d) AUGUST

Average Rainfall$_{(1970-73)}$ / Average Rainfall$_{(1966-69)}$

COUNTY	0-20%	21-40%	41-60%	61-80%	81-100%	101-120%	121-140%	141-160%	161-180%	181-200%	201%+	AVG %
Floyd					4	6						102
Hale			6	3	1							60
Lamb			5	5								60
Bailey					10							90
Briscoe				4	4	2						86
Castro				5	5							80
Cochran				5	5							80
Crosby				7	3							76
Hockley			2	7	1							68
Lubbock			2	6	2							70
Lynn				1	1	2	3	2	1			124
Parmer					10							90
Swisher				6	4							78
Terry			5	2	2	1						68

Mean percentage change of 3 seeded counties 74

Mean percentage change of 11 unseeded counties 83

Table 4. (Continued)

e) SEPTEMBER

Average Rainfall$_{(1970-73)}$ / Average Rainfall$_{(1966-69)}$

COUNTY	0-20%	21-40%	41-60%	61-80%	81-100%	101-120%	121-140%	141-160%	161-180%	181-200%	201%+	AVG %
Floyd							1	2	3	4		170
Hale					3	2	2	2	1			122
Lamb							1	5	4			156
Bailey						5	4	1				122
Briscoe					4	3	2	1				110
Castro						3	4	3				130
Cochran							3	4	3			150
Crosby										4	6	212
Hockley						1	3	2	4			148
Lubbock						2	1	1	3	1	1	141
Lynn								1	1	2	6	206
Parmer					3	7						104
Swisher					9	1						92
Terry						1	2	2	2	2	1	160

Mean percentage change of 3 seeded counties 149

Mean percentage change of 11 unseeded counties 143

f) OCTOBER

Average Rainfall$_{(1970-73)}$ / Average Rainfall$_{(1966-69)}$

COUNTY	0-20%	21-40%	41-60%	61-80%	81-100%	101-120%	121-140%	141-160%	161-180%	181-200%	201%+	AVG %
Floyd				3	3	4						92
Hale				2	3	5						96
Lamb				2	2	5	1					100
Bailey					9	1						92
Briscoe						5	5					120
Castro				2	2	3	2	1				106
Cochran					10							90
Crosby				3	5	2						88
Hockley				6	4							78
Lubbock				6	4							78
Lynn					5	4	1					102
Parmer					2	8						106
Swisher						8	2					104
Terry				8	2							74

Mean percentage change of 3 seeded counties 96

Mean percentage change of 11 unseeded counties 94

In summary, in five of the six months considered in this study, the areal percentage change in rainfall was in a negative direction, i.e., the average, county-wide rainfall was less in the seeded period than in the base period. This was true for both target and control regions alike. Even though the differences between average rainfall of the two periods at each of the 22 stations reveal a general diminution of rainfall amounts within Hale, Floyd, and Lamb counties in the period 1970-73, the above analysis of areal percentage change does not tend to imply that this diminution was due to cloud seeding activities. On the contrary, since this diminution occurred in the non-seeded region as well, the available evidence suggests no significant effect. The accompanying tables of areal percentage change in rainfall intimate that such a reduction in rainfall as that characterizing the seeding period of 1970-73 could have occurred anyway, even if cloud seeding had not been done.

2. Application of Analysis of Variance Upon Monthly Rainfall

With reference to Chapter III the main objective of the analysis of variance is to estimate the effect of cloud seeding on rainfall. This estimated difference due to cloud seeding is +0.054 inches with a standard error of 0.17 inches, and this difference (although positive, i.e., in favor of cloud seeding) is statistically and practically quite insignificant. We should note that the overall mean monthly rainfall was 2.45 inches.

From the point of view of monitoring the reasonableness of the analysis of variance it is of some interest to estimate and test the magnitude in the rainfall variation ascribable to the other sources of variation listed in Chapter III. These are first set out in Table 5 and subsequently discussed.

All sources of variation account for approximately 64% of the total variation in monthly rainfall. It is evident that there is considerable variation among years and months, and also that month-to-month variation (i.e., the monthly rainfall pattern) changes from year-to-year. It is also evident that there is some variation among stations but essentially no variation due to seeding.

In order to monitor the possibility that the analysis of total monthly rainfall may be biased by unusually heavy precipitation, we have also performed an analysis of variance for the monthly rainfall with daily contributions over 5 inches excluded. The results of this analysis are almost identical to those of Table 5 and are not reproduced here.

A third variable, called "storminess," consisting of the number of days the rainfall exceeded 1/2 inch, also produced very similar results.

Table 5. Analysis of Variance of Rainfall Data

SOURCE	DEGREES OF FREEDOM	MEAN SQUARE	F-RATIO
Total	1055		
All Sources	69	363,793	25.62
Between Years	7	697,072	49.08**
Between Months	5	508,579	35.81**
Interaction Year x Month	35	486,475	34.25**
Between Stations	21	27,591	1.94+
Contrast due to Seeding	1	1,437	.10
Residual	986	14,202	

** Statistically significant at .01% level

+ Statistically significant at 1% level

3. Examination of Observed and Expected Rainfall Frequencies

To supplement the results of the analysis of variance, it was desirable to examine differences between the rainfall frequencies and employ the X^2 goodness-of-fit test for that purpose. The frequency distributions of seeded and non-seeded stations were compared for the period 1970-73 when seeding was applied to the three counties. The results are set out in Table 6.

Table 6. Results of a X^2 goodness-of-fit test of the distribution of monthly rainfall of the six seeded and sixteen unseeded stations for the test period 1970-73.

H_o: Monthly rainfall distributions of the two classes of stations are not significantly different.

Month	Observed X^2 Value	d.f probability	d.f	$X^2_{.95}$	Result
May	11.82	$X^2_{5,.965}$	5	11.07	reject H_o
Jun	4.56	$X^2_{6,.40}$	6	12.59	unable to reject H_o
Jul	7.14	$X^2_{6,.69}$	6	12.59	unable to reject H_o
Aug	6.14	$X^2_{6,.59}$	6	12.59	unable to reject H_o
Sep	1.66	$X^2_{4,.20}$	4	9.49	unable to reject H_o
Oct	1.14	$X^2_{3,.22}$	3	7.81	unable to reject H_o

It will be noted that in all months except May the X^2 test is not capable of detecting any significant difference between the two distributions. During May it was observed that the area of maximum rainfall occurred within the seeded region (compare with Fig. 3), and the seeded stations received larger amounts of rainfall on the average during that 4-year period more frequently than the unseeded stations. However, the X^2 criterion is just barely significant at the 5% level and in view of the fact that only one month out of a total of six months showed a barely significant result no major importance can be attached to this result. It is, however, of interest to note that in this experiment the month of May indicates at least a potential of an effect by seeding.

B. ANALYSIS OF HAIL

1. Tabulation of Crop-Hail Actuarial Association Statistics

Table 7 shows losses as a per cent of liability that were paid by private insurance companies in 1967-73 for three counties in the hail suppression area, nine counties not in the hail suppression area, and for the total 12-county area. These data were developed from statistics provided by the Crop-Hail Actuarial Association.

For the years 1967-69, the hail suppression program had not begun in this area. For these years, the damage value for counties that will be in the hail-suppression program is larger for two out of three years. In 1967 and 1968 the damage value is similar between the two areas, while in 1969 it is about twice as large in the suppression area as in the non-suppression area. Data for these years indicate the magnitude of yearly and area fluctuations in weather-related data.

During the years of hail suppression activity, the damage value for the suppression area was larger in 1970 and 1971 than in other years, and smaller in 1972 and 1973. Again, there is considerable yearly and area fluctuations in the damage values. This information indicates the general magnitude and fluctuations in hail damages but provides little insight into the effectiveness of the hail-suppression activity.

2. Tabulation of Federal Crop Insurance Corporation Statistics

From Federal Crop Insurance Corporation statistics, sufficient data are provided so that per acre lint loss due to hail damage can be estimated. Table 8 shows hail damage (lint loss) to cotton per acre insured for three counties in the hail-suppression area and nine counties not in the hail-suppression area. Hail-suppression activities have been conducted since 1970. The hail damage values in Table 8 are similar to Table 7 data in that they show considerable county and yearly fluctuations of hail losses. A cursory look at the data indicates that hail losses have been less, generally, since 1970 for both areas. For the years preceding hail-suppression activities, for 1968 through 1970, insured hail losses were greatest in the suppression area, while from 1971 through 1973 they were less, compared to the non-suppression area.

Table 9 presents cotton acres insured by the Federal Crop Insurance Corporation by county and year. The nature of the sample (changing annually in acreage and farmers insuring) places limitations on effectiveness and appropriateness of a statistical analysis. Total harvested acres of cotton in the hail-suppression area were 281,800, 422,900, and 440,000 for 1971, 1972, and 1973, respectively. Acres of cotton harvested in the nine counties not included in the suppression area were 899,800, 913,400, and 957,550 for 1971, 1972 and 1973, respectively. Over all 12 counties, the percent that Federal Crop Insured acres were of total harvested acres is 14, 13, and 14 for 1971, 1972 and 1973, respectively. These years are representative of the seven years of data presented.

Table 7. Cotton losses as a per cent of total liability for private insurance companies delineated by suppression, non-suppression and total areas; Texas High Plains, 1967-73[a]

Year	Losses as percent of liability		
	Suppression area[b]	Non-suppression area[c]	Total area[d]
1967[e]	9.84	10.77	10.47
1968[e]	11.70	9.94	10.50
1969[e]	25.39	13.66	16.07
1970[f]	4.82	2.20	2.80
1971[f]	8.34	7.68	7.78
1972[f]	5.08	11.83	10.56
1973[f]	2.74	3.65	3.55

[a] Based on published statistics provided by the Crop-Hail Actuarial Association.

[b] Hale, Lamb, and Floyd Counties.

[c] Bailey, Briscoe, Castro, Cochran, Crosby, Hockley, Lubbock, Parmer, and Swisher Counties.

[d] All counties in b and c above.

[e] A year in which hail suppression activities were not conducted.

[f] A year with hail suppression activities.

Table 8. Hail damage to cotton per acre insured; Texas High Plains, 1967-73[a]

County	Lint loss per acre insured (lbs.)						
	1967	1968	1969	1970	1971	1972	1973
Floyd[b]	5.22	161.31	31.72	26.33	58.26	1.76	0.59
Hale[b]	16.67	104.41	59.84	7.50	22.43	11.88	0.46
Lamb[b]	67.53	45.67	68.69	2.82	6.14	21.86	1.33
Average[d]	37.19	83.30	58.07	9.14	23.07	13.00	.80
Bailey[c]	62.78	15.10	52.99	0.00	7.65	14.13	0.86
Briscoe[c]	10.20	32.07	5.27	7.85	23.86	45.04	5.89
Castro[c]	92.92	69.42	50.28	4.80	36.59	21.66	5.82
Cochran[c]	52.75	5.34	14.50	8.63	1.26	0.00	0.00
Crosby[c]	0.52	71.58	97.21	4.80	12.85	0.18	3.52
Hockley[c]	22.05	4.40	29.30	0.28	19.02	44.52	0.71
Lubbock[c]	21.23	55.47	45.36	0.62	15.94	17.94	5.43
Palmer[c]	85.18	20.79	21.93	9.32	21.31	39.26	0.48
Swisher[c]	40.98	130.05	45.94	11.95	83.46	11.29	29.37
Average[d]	37.87	57.09	46.40	3.64	24.53	19.39	4.89

[a] Derived from data provided by the Federal Crop Insurance Corporation.

[b] Counties in the hail suppression area with suppression activities beginning in 1970.

[c] Counties not in the hail suppression area.

[d] Weighted average considering acreage in each county.

Table 9. Acres of cotton insured by the Federal Crop Insurance Corporation, Texas High Plains; 1967-73[a]

County	Acres Insured							
	1967	1968	1969	1970	1971	1972	1973	Average
Floyd[b]	5,067	9,825	23,344	19,303	14,916	18,185	17,862	15,500
Hale[b]	10,231	18,951	50,336	38,932	24,899	26,691	26,176	28,031
Lamb[b]	12,255	31,002	49,578	42,401	30,050	26,446	23,671	30,772
Total	27,553	59,778	123,258	100,636	69,865	71,322	67,709	74,303
Bailey[c]	1,976	3,194	4,773	3,692	4,425	6,230	5,889	4,311
Briscoe[c]	1,413	1,941	2,704	1,808	1,582	2,408	2,750	2,087
Castro[c]	4,441	12,757	18,729	15,504	12,204	12,318	6,415	11,767
Cochran[c]	1,552	1,883	1,702	1,768	2,408	2,293	1,902	1,930
Crosby[c]	2,331	2,928	8,249	6,711	7,451	11,846	18,200	8,245
Hockley[c]	4,100	6,732	9,217	8,378	8,227	11,635	25,089	10,483
Lubbock[c]	16,862	32,917	47,830	43,902	42,902	49,440	66,325	42,864
Palmer[c]	2,962	3,684	5,765	4,573	3,584	3,218	2,276	3,723
Swisher[c]	4,663	8,532	19,901	12,750	8,433	8,548	5,257	9,726
Total	40,300	74,568	118,870	98,953	91,216	107,936	134,103	95,135

[a] Derived from data provided by the Federal Crop Insurance Corporation.

[b] Counties in the hail suppression area with suppression activities beginning in 1970.

[c] Counties not in the hail suppression area.

Table 10 shows acres of cotton where the Federal Crop Insurance Corporation paid damages due to hail. This relates to the total acres insured as presented in Table 9.

The analysis of ASCS and Federal Crop Insurance Corporation data was done considering Floyd, Hale and Lamb as the test area and Bailey, Briscoe, Castro, Cochran, Crosby, Hockley, Lubbock, Parmer and Swisher the non-program area. Since spring and summer weather patterns move predominantly from the southwest toward the northeast, it appeared possible that the effect of hail suppression might be experienced on counties north and east of the program area. Therefore, the hail suppression area was confined to Lamb and Hale counties, with Floyd, Briscoe, Castro, and Swisher deleted completely. This adjustment did not change the results of the statistical analysis, i.e., no statistically significant difference in rainfall or hail damage was evident between Lamb and Hale counties and Bailey, Cochran, Crosby, Hockley, Lubbock and Palmer counties.

3. Tabulation of U.S. Department of Agriculture Records (ASCS)

This section presents general summation of information and results of the statistical analysis.

Tables 11-13 indicate acres of cotton, total production, and total weather losses for 12 counties in the Texas High Plains. The information is for three counties in the hail-suppression area and nine counties outside. Each table contains information for a separate year beginning with 1971 and ending with 1973. Table 14 contains similar aggregated data by suppression area and non-suppression for 1971 through 1973 and summation over all three years.

Producer records of weather related losses in 1971 were not available for Hale County (Table 11). Weather Losses in 1971, as a percent of adjusted production (actual production plus estimated weather losses), ranged from 30 to 40 percent for the suppression counties and from 4 to 62 percent for the non-suppression counties. The average percentage loss in output due to weather was 37.12 in the suppression area compared to 36.84 percent in the non-suppression area.

In 1972 (Table 12), weather losses as a percent of adjusted production were much less than in 1971, i.e., 15.83 percent in the suppression area compared to 16.86 in the non-suppression area. This loss was even less in 1973 averaging 1.55 percent in the suppression area and 3.22 percent in the non-suppression area (Table 13). Data in Table 14 indicate that over the three year period, weather related loss as a percent of adjusted output was 14.12 and 17.05 in the suppression and non-suppression areas, respectively.

This information, while interesting and providing a slight hint of less losses in the suppression area, must be considered concurrently with the limitations. Namely, the losses referred to are all weather-related losses including hail, rain, freeze, drouth, wind, etc. To

Table 10. Acres of cotton where damages were paid; Texas High Plains, 1966-73[a]

County	Acres Indemnified						
	1967	1968	1969	1970	1971	1972	1973
Floyd[b]	693	7,719	9,563	4,690	11,199	1,459	165
Hale[b]	2,847	11,791	29,104	4,313	9,788	4,727	75
Lamb[b]	7,084	10,610	35,982	7,447	12,836	7,563	292
Total	10,624	30,120	74,649	16,452	33,823	13,749	532
Bailey[c]	945	535	2,750	780	2,016	1,226	242
Briscoe[c]	60	830	1,241	253	1,288	659	85
Castro[c]	3,098	6,808	12,086	2,953	7,670	3,195	424
Cochran[c]	635	217	1,209	1,017	1,768	388	0
Crosby[c]	92	1,333	4,864	764	5,538	218	520
Hockley[c]	828	400	3,452	804	6,169	4,840	444
Lubbock[c]	2,241	10,284	21,468	1,586	23,691	10,819	2,105
Palmer[c]	1,295	658	2,195	808	1,830	1,348	33
Swisher[c]	1,489	6,468	12,126	2,609	6,704	1,686	1,146
Total	10,683	27,533	61,391	11,574	56,674	24,378	4,999

[a] Derived from data provided by the Federal Crop Insurance Corporation.

[b] Counties in the hail suppression area with suppression activities beginning in 1970.

[c] Counties not in the hail suppression area.

Table 11. Summary of weather-related losses of cotton lint in 1971 for 12 counties in the Texas High Plains.

County		Planted Acres (a) (000)	Harvested Acres (a) (000)	Total Production (a) (000) Bales	Weather Losses (b) (000) Bales	Adjusted Production (c) (000)	Percentage Loss (d) %	Loss/Acre Planted #'s	Number (e) of observations
Treatment Group:									
Floyd	1	103.70	93.30	51.10	21.88	72.98	29.98	101.28	345
Hale	2	161.50	153.00	96.10	N/A	N/A	N/A	N/A	-0-
Lamb	3	178.10	165.00	88.30	60.40	148.70	40.62	162.78	1,659
Total		281.80 (f)	258.80 (f)	139.40 (f)	82.28 (f)	221.68 (f)	37.12 (f)	140.15 (f)	
Control Group:									
Bailey	4	73.70	57.10	29.40	31.04	60.44	51.36	202.16	793
Briscoe	5	26.50	25.80	12.40	.70	13.10	05.34	12.74	28
Castro	6	51.20	44.00	20.30	6.75	27.05	03.70	63.29	170
Cochran	7	82.00	77.90	33.80	29.80	63.60	46.85	174.43	428
Crosby	8	129.90	127.30	77.60	48.64	126.24	38.53	179.72	664
Hockley	9	201.00	192.20	88.40	95.31	183.71	51.88	227.61	1,391
Lubbock	10	234.20	227.50	155.90	26.22	182.12	14.40	53.75	502
Parmer	12	45.50	43.20	22.00	4.67	26.67	17.52	49.28	111
Swisher	13	55.80	36.80	12.70	20.84	33.54	62.13	179.26	429
Total		899.80	831.80	452.50	263.97	716.47	36.84	140.82	4,516
Overall Total		1.181.60 (f)	1,090.10 (f)	591.90 (f)	346.25 (f)	938.15 (f)	36.91 (f)	140.82 (f)	6,520

(a) From Texas Crop and Livestock Reporting Service.

(b) From County ASCS records. Weather losses = (Adjusted yield x planted acres) - (Actual yield x harvested acres)

(c) Total Production + weather losses

(d) Weather losses/adjusted production

(e) Each observation is an individual ASCS damage claim

(f) Totals do not include Hale County for which weather loss data was unavailable for 1971.

Table 12. Summary of weather-related losses in cotton lint in 1972 for 12 counties in the Texas High Plains.

County		Planted Acres (a) (000)	Harvested Acres (a) (000)	Total Production (a) (000) Bales	Weather Losses (b) (000) Bales	Adjusted Production (c) (000)	Percentage Loss (d) %	Loss/Acre Planted #'s	Number (e) of observations
Treatment Group:									
Floyd	1	108.80	97.40	125.00	4.19	129.19	03.25	18.51	170
Hale	2	161.50	149.10	142.80	27.36	170.16	16.08	81.33	706
Lamb	3	172.60	144.40	110.90	39.67	150.59	26.36	110.37	1,091
Total		442.90	390.90	378.70	71.24	449.94	15.83	77.21	1,967
Control Group:									
Bailey	4	92.90	82.50	72.30	7.94	80.24	9.90	41.05	276
Briscoe	5	26.60	22.30	20.85	3.55	24.40	14.56	64.12	118
Castro	6	48.60	40.40	35.00	15.74	50.74	31.03	155.50	611
Cochran	7	82.40	76.10	75.60	5.11	80.71	06.33	29.76	104
Crosby	8	132.70	120.20	151.50	2.44	153.94	01.58	8.84	62
Hockley	9	195.80	168.70	121.40	61.86	183.26	33.75	151.65	922
Lubbock	10	241.20	220.90	233.30	42.43	275.73	15.39	84.44	833
Parmer	12	43.20	36.80	33.35	12.69	46.04	27.56	140.99	533
Swisher	13	50.00	44.20	45.85	8.30	54.15	15.32	79.65	291
Total		913.40	812.10	789.15	160.06	949.21	16.86	84.11	3,750
Overall Total		1,356.30	1,203.00	1,167.85	231.30	1,399.15	16.53	81.86	5,717

(a) From Texas Crop and Livestock Reporting Service.

(b) From County ASCS records. Weather losses = (Adjusted yield x planted acres) - (Actual yield x harvested acres)

(c) Total production + weather losses

(d) Weather losses/adusted production

(e) Each observation is an individual ASCS camage claim

Table 13. Summary of weather-related losses in cotton lint in 1973 for 12 counties in the Texas High Plains

County		Planted Acres (a) (000)	Harvested Acres (a) (000)	Total Production (a) (000) Bales	Weather Losses (b) (000) Bales	Adjusted Production (c) (000)	Percentage Loss (d) %	Loss/Acre Planted # 's	Number of Observations (e)
Treatment Group:									
Floyd	1	123.50	122.10	143.40	2.26	145.66	1.55	8.77	113
Hale	2	153.20	149.50	162.50	4.83	167.33	2.89	15.13	261
Lamb	3	167.30	165.70	153.20	.12	153.32	.08	.35	2
Total		444.00	437.30	459.10	7.21	466.31	1.55	7.79	376
Control Group:									
Bailey	4	88.10	86.80	73.00	4.36	77.36	5.63	23.73	238
Briscoe	5	31.20	30.90	31.40	.54	31.94	1.69	8.29	37
Castro	6	39.70	39.00	32.90	4.88	37.78	12.92	59.04	358
Cochran	7	88.60	88.50	80.70	1.32	82.02	1.61	7.16	57
Crosby	8	156.10	155.30	186.90	2.27	189.17	1.20	6.98	64
Hockley	9	214.90	214.70	206.40	2.69	209.09	1.29	6.00	94
Lubbock	10	262.40	262.10	310.00	4.60	314.60	1.46	8.42	187
Parmer	12	30.60	30.10	25.00	5.26	30.26	17.38	82.47	500
Swisher	13	45.95	42.60	33.30	6.64	39.94	16.63	69.41	335
Total		957.55	950.00	979.60	32.56	1,012.16	3.22	16.32	1,870
Overall Total		1,401.55	1,387.30	1,438.70	39.77	1,478.47	2.69	13.62	2,246

(a) From Texas Crop and Livestock Reporting Service.

(b) From County ASCS records. Weather losses = (Adjusted yield x planted acres) - (Actual yeild x harvested acres).

(c) Total production + weather losses.

(d) Weather losses / adjusted production.

(e) Each observation is an individual ASCS damage claim.

Table 14. Summary of weather-related losses in cotton lint in 1971 - 1973 for treatment and control groups on the Texas High Plains

County	Planted Acres (a) (000)	Harvested Acres (a) (000)	Total Production (a) (000) Bales	Weather Losses (b) (000) Bales	Adjusted Production (c) (000)	Percentage Loss (d) %	Loss/Acre Planted # 's	Number of Observations (e)
1971:								
Treatment	281.80 (f)	258.30 (f)	139.40 (f)	82.28 (f)	221.68 (f)	37.12 (f)	140.15 (f)	2,004
Control	899.80	831.80	452.50	263.97	716.47	36.84	140.82	4,516
Total	1,181.60	1,090.10	591.90	346.25	938.15	36.91	140.66	6,520
1972:								
Treatment	442.90	390.90	378.70	71.24	449.94	15.83	77.21	1,967
Control	913.40	812.10	789.15	160.06	949.21	16.86	84.11	3,750
Total	1,356.30	1,203.00	1,167.85	231.30	1,399.15	16.53	81.86	5,717
1973:								
Treatment	444.00	437.30	459.10	7.21	466.31	1.55	7.79	376
Control	957.55	979.60	979.60	32.56	1,012.16	3.22	16.32	1,870
Total	1,401.55	1,438.70	1,438.70	39.77	1,478.47	2.69	13.62	2,246
1971-73:								
Treatment	1,168.70 (f)	977.20 (f)	977.20 (f)	160.73	1,137.93 (f)	14.12 (f)	66.01 (f)	4,347
Control	2,770.75	2,221.25	2,221.25	456.59	2,677.84	17.05	79.10	10,136
Total	3,939.45	3,198.40	3,680.40	617.32	3,815.77	16.18	75.22	14,483

(a) From Texas Crop and Livestock Reporting Service.

(b) From County ASCS records. Weather losses = (Adjusted yield x planted acres) - (Actual yeild x harvested acres).

(c) Total production + weather losses.

(d) Weather losses /adjusted production.

(e) Each observation is an individual ASCS damage claim.

(f) Total do not include Hale County for which weather loss data was unavailable for 1971.

isolate losses attributable to hail and draw inferences about the suppression program, a statistical analysis is required.

4. Statistical Analysis of the U. S. Department of Agriculture Records (ASCS)

As indicated in Chapter III the analysis of these data will be concerned with:

(1) An estimation of the effect of cloud seeding on the percentage loss of cotton incurred by operators who report losses due to hail damage, and

(2) An estimation of the effect of cloud seeding on the percentage of cotton operators reporting any cotton losses due to hail.

A total of 7,516 operators reported losses due to weather and reported hail as one of the causes of their losses. Their average percentage loss was almost exactly 60% of thier expected cotton harvest. The estimated reduction in this percentage due to seeding was estimated at almost exactly 6% with a standard error of 6.4%. From a practical point of view this reduction is disappointing and probably would not pass a cost-benefit analysis. From a statistical point of view, it will be seen from the attached analysis of variance (Table 15) that the effect of seeding when tested against the residual mean square is highly significant. However, as has been pointed out in Chapter III, the residual mean square is invalid as an error because of reasons explained there. A valid error is provided by the interaction of counties by years within county groups and when tested against this it is quite insignificant. From a statistical point of view, it should be noted that because of the imbalance of the data, the latter test is not an exact F-test.

In order to monitor the reasonableness of the analysis of variance given in Table 15, it should be noted that the invalidity of the residual as an experimental error is confirmed by the highly significant interaction of counties by years within county groups. Using the latter as an error, there is still an indication of significant differences between the percentage cotton losses encountered in different years. There is also an indication of significant differences between the cotton losses encountered in different counties within the same county groups.

5. Percentages of Operators Reporting Hail Losses

For the three cloud seeded counties (Floyd, Hale, and Lamb) the average percentage of operators reporting hail losses is 15.0%. For the 9 control counties (Bailey, Briscoe, Castro, Cochran, Crosby, Hockley, Lubbock, Parmer, and Swisher) the average is 18.5%. Therefore, the effect of seeding is assessed through a reduction in the percentage of 3.5%. However, this reduction is again from a practical point of view, and from a statistical point of view insignificant. It is difficult to estimate the standard error of this

Table 15. Analysis of Variance of Percent Cotton Losses

Source of Variation	Degrees of Freedom	Mean Square
Between Years	2	9.8873
Between Counties within County Groups	10	4.0651
Interaction of Counties by Years Within County Groups	20	1.1400
Cloud Seeding Contrast	1	1.0560
Losses Due to Causes Other Than Hail	6	4.9938
Residual	7476	0.0652

Table 16. Analysis of Variance of Percentages of Operators Reporting Hail-Losses

Source of Variation	Degrees of Freedom	Mean Square
Between Years	2	0.09206
Between Counties Within County Groups	10	0.01986
Cloud Seeding Contrast	1	0.00563
Residual	21	0.01665

difference because of the imbalance of the data but it is roughly assessed as 5.1%.

In order to monitor the reasonableness of the analysis of variance, this is set out in Table 16. From a statistical point of view, it should be noted that this analysis of variance is one for the arcsin transformation of the percentages. There are no significant differences except those between years indicating quite reasonably that the incidence of hail storms differs from year to year. However, it is of interest to note that there are no systematic differences between counties persistent over the three years. This is in contrast to the analysis under (a) where county differences were established between the average percentage losses of cotton incurred by operators reporting hail damage.

6. Combination of evidence from analysis (4) and (5)

We now turn to a combination of the evidence of the two statistical analyses presented in (4) and (5) above.

Two methods of combining the evidence were used. The first is essentially a computation of an average proportion cotton loss suffered per operator operating in the seeded versus the nonseeded counties. The estimated reduction due to seeding in this proportional loss is 4.3%. However, the probability for this to have occurred by chance is 0.27. This probability should in fact be smaller than .05 if the difference could be claimed as being statistically significant.

As a monitoring test procedure of combining the evidence in the analysis (4) and (5) we have carried out a procedure of "combining statistical evidence" recommended by the renowned statistician R. A. Fisher and widely used. Technically it consists of converting the evidence contained in each analysis into a chi-square statistic and then adding the two chi-square statistics. The probability of the "beneficial" effect due to seeding to be due to chance on this analysis is 0.20 and is again considerably larger than the .05 indicating that it cannot claim to be statistically significant.

7. Analysis of Federal Crop Insurance Data

We now turn to the statistical analysis of the Federal Crop Insurance Corporation data. These data are summarized in Table 9. A preliminary investigation revealed the possibility of unreliable figures for Floyd, Briscoe, Castro, and Swisher counties. These were omitted from the analysis for seeding effect on crop losses due to hail. A general linear regression model was used to gauge the loss per acre data in terms of categorical classification variables for year, county and seeding effect.

The mean loss was found to be 23.4 pounds per acre insured. The regression model accounted by 49% of the variation with a residual standard deviation of 21.3 pounds per acre. The analysis of variance (Table 17) shows the yearly variation is the only significant factor; there is no indication of significantly different losses due to seeding effect or of the losses encountered between different counties within the seeding group.

Table 17. Analysis of Variance for Federal Crop Insurance Data

Source of Variation	Degrees of Freedom	Mean Square
Between year	7	1.7082×10^3
Between Counties Within County Groups	8	3.6971×10^2
Cloud seeding contrast	1	125.5133
Residual	47	453.6340

These data also contain the problem of being based only on a sample of those operators who were insured and reported losses. An analogous percentage analysis as was performed in Section IV, 2(e) can be done here to test the seeding effect against the ratio of acreage of the operators reporting losses to the total acreage in the counties for the years 1966 to 1973. The arcsin transformation on the ratio is given in the analysis of variance (Table 18). For the two seeded counties (Hale, Lamb), the average reporting losses due to hail was 52% whereas in the six control counties (Bailey, Cochran, Crosby, Hockley, Lubbock, Parmer) the average percentage reporting losses was 46.6%. Superficially, the seeding appears to have increased the percentage of those reporting losses by 5.4%. However, this increase is not statistically significant and has an estimated standard error of 8.7%.

The analysis of variance (Table 18) indicates only the variation between years is a significant factor with no significance indicated due to either seeding effects or variations between the counties within county groups (seeded and unseeded). These results remain consistent with those in previous analyses.

Table 18. Variance of Percentages of Acreage with Operators Reporting Hail Losses

Source of Variation	Degree of Freedom	Mean Square
Between years	7	0.84378
Between counties within county groups	8	0.11445
Cloud seeding contrast	1	0.05502
Residual	44	0.09282

Since the analysis of ASCS and Federal Crop Insurance Corporation data do not indicate a statistically significant reduction in hail damages due to the program, there is no scientific basis for establishing any economic returns to the program.

8. Analysis of Hail Intensity Data

Finally we turn to the analysis of the hail intensity data. These are summarized in Table 19. The average hailstone diameter for the observations in this data set is 0.69 inches with a standard error of 0.012. The overall analysis accounts for the 52% of the total variation, however, the overall regression is not statistically significant at the 5% level. Furthermore, none of the individual sources of variation is statistically significant. The estimated effect due to cloud seeding is actually an increase in hail diameter by .0089 inches, however, since this is a very small amount and moreover is not statistically significant, this number is meaningless.

Table 19. Analysis of Variance for Average Size Hail Diameters

Source of Variation	Degrees of Freedom	Mean Square
Between years	7	0.06767
Cloud seeding contrast	1	0.15192
Between counties within county groups	13	0.07925
Residual	31	0.05203

CHAPTER V. AN OPERATIONAL PREDICTION MODEL FOR THE OCCURRENCE AND SEVERITY OF HAIL

A. INTRODUCTION

For operational purposes one finds it useful to use one-dimensional models. At Texas A&M University we have researched only with adiabatic one-dimensional models. The entraining model, which operationally has been found more useful, can be obtained in a rather simple way. However, entrainment has received such a varied treatment that we are faced with a decision problem. The picture is clearing up rather well as can be seen from the discussion that follows. In order to keep it brief the discussion will be restricted to the continuity and momentum equations only.

B. THE CONTINUITY EQUATION

In customary entraining models the mass conservation is treated in terms of vertical mass flux. The latter is then parameterized mostly on the basis of observations or laboratory measurements. There is no agreement on a best method of parameterization. We view this problem in the following manner:

Taking an axisymmetric, anelastic form of the continuity equation,

$$\frac{\partial}{\partial r}\left(\rho u r\right) + r\frac{\partial}{\partial z}\left(\rho w\right) = 0, \quad \rho \equiv \rho(z)$$

and assuming a "top-hat" profile, viz.,

$$w = \begin{cases} w(z), & 0 \le r \le r_\circ \\ 0, & r > r_\circ \end{cases}$$

we integrate in the horizontal to obtain

$$\frac{\partial}{\partial t}\left(r_\circ^2\right) + w r_\circ^2 \frac{\partial}{\partial z}\left(\ln \rho r_\circ^2 w\right) = \phi(z,t). \tag{7}$$

Here r is the radial distance from the axis of symmetry, z is the height, u and w, respectively, are the radial and the vertical components of velocity, ρ is the air density, and $\phi(z,t)$ is a time-dependent profile function. Wisner, Orville, and Myers (1972) use

$$\phi(z,t) = 2r_o^2\alpha|w| \left\{1+\left(\frac{\partial r_o}{\partial z}\right)^2\right]^{\frac{1}{2}} \tag{8}$$

This form of ϕ (z,t) was obtained by heuristic arguments and as such is not dynamically binding. In fact Squires and Turner (1962) use

$$\phi(z,t) = 2r_o\alpha|w| \tag{9}$$

from some empirical considerations.

C. THE MOMENTUM EQUATION

Using the anelastic form of the momentum equation written in terms of fluxes

$$\rho\frac{\partial w}{\partial t} + \frac{1}{r}\frac{\partial}{\partial r}\left(\rho rwu\right) + \frac{\partial}{\partial z}\left(\rho w^2\right) = \rho g\left(\frac{\theta_v - \theta_{v_o}}{\Theta} - \xi\right),$$

where the unfamiliar symbols are Θ , the basic state potential temperature, and ξ the mixing ratio of the condensed phase (cloud water, rain, and hail). We integrate and rearrange to obtain

$$\frac{\partial w}{\partial t} + w\frac{\partial w}{\partial z} = g\left[\frac{\theta_v - \theta_{v_o}}{\Theta} - \xi\right] - \frac{\rho w}{r_o}\,\phi(z,t) + \frac{2}{\rho r_o^2}\,h(z,t) \tag{10}$$

where $\phi(z,t)$ is the profile function coming from the continuity equation and h(z,t) enters through the last integration. It is to be seen from (10) that we have an added degree of freedom which has been recognized in the literature. Silverman and Glass (1973) use ϕ (z,t) as shown in (9) and

$$h(z,t) = \frac{4K_m w}{\rho}$$

where K_m is an exchange coefficient. This last form was picked from a study by Priestley (1953).

D. PROFILE FUNCTIONS FOR OTHER QUANTITIES

We have equations, similar to (10) for cloud water, precipitation and temperature, the profile functions of which are neither obvious nor discussed in the literature. A customary assumption is to introduce the profile function $\phi(z,t)$ and ignore any additional degree of freedom of the particular quantity in question. At this time this appears to be a good starting point for our efforts.

E. THE ADIABATIC SYSTEM AND ITS IMPLICATION IN OUR OPERATIONAL EFFORTS

The adiabatic system is obtained by setting all the profile functions to zero. Although, quantitatively, the results of this system are likely to be quite different from those of the system we are looking for, we are presenting some of them for illustration of the type of results that might be expected from operational-model runs.

The results are displayed in the form of a set of time-height cross-sections. The model refers to the Oklahoma typical severe-storm sounding which easily permits a vertical velocity of 30 m s^{-1}. Figure 9 gives the time-height cross-section of vertical velocity, w, where the isopleths are labelled in units of m s^{-1}. Figure 10 shows the time-height cross-section of (the mixing ratio of the total condensed phase) and the isopleths are labelled in units of g kg^{-1}; Figs. 11 and 12 show the mixing ratios of liquid and solid precipitation, respectively; and Fig. 13 shows the time-height cross-section of radar reflectivity factor in units of mm^6m^{-3}.

F. RADAR ECHOES VS PRECIPITATION PHENOMENA

Radar-echo sketches obtained from the Littlefield radar during May-August, 1974, were examined for possible association between some radar-echo parameter, and precipitation and other significant weather phenomena. For simplicity's sake two parameters were considered: (1) number of radar echoes, and (2) the area covered by radar echoes, the echoes having been recorded above a fixed threshold. A preliminary examination of the radar-echo patterns, as well as the availability and space-time resolution of the weather-element observations, showed rather limited significance of the number of echoes. The area covered by echoes appeared more promising as an indicator of the occurrence and intensity of the significant phenomena.

For the sake of objectivity, analysis was restricted to the circular area of 40-mi radius around Littlefield. The area covered by all the echoes within this area was measured with a planimeter and this area was then expressed as a percentage of the 40-mi circle. Since radar observations were taken at irregular intervals, all the observations were at first tabulated (table not shown). The observations were then classified basically into two parts: (1) those taken

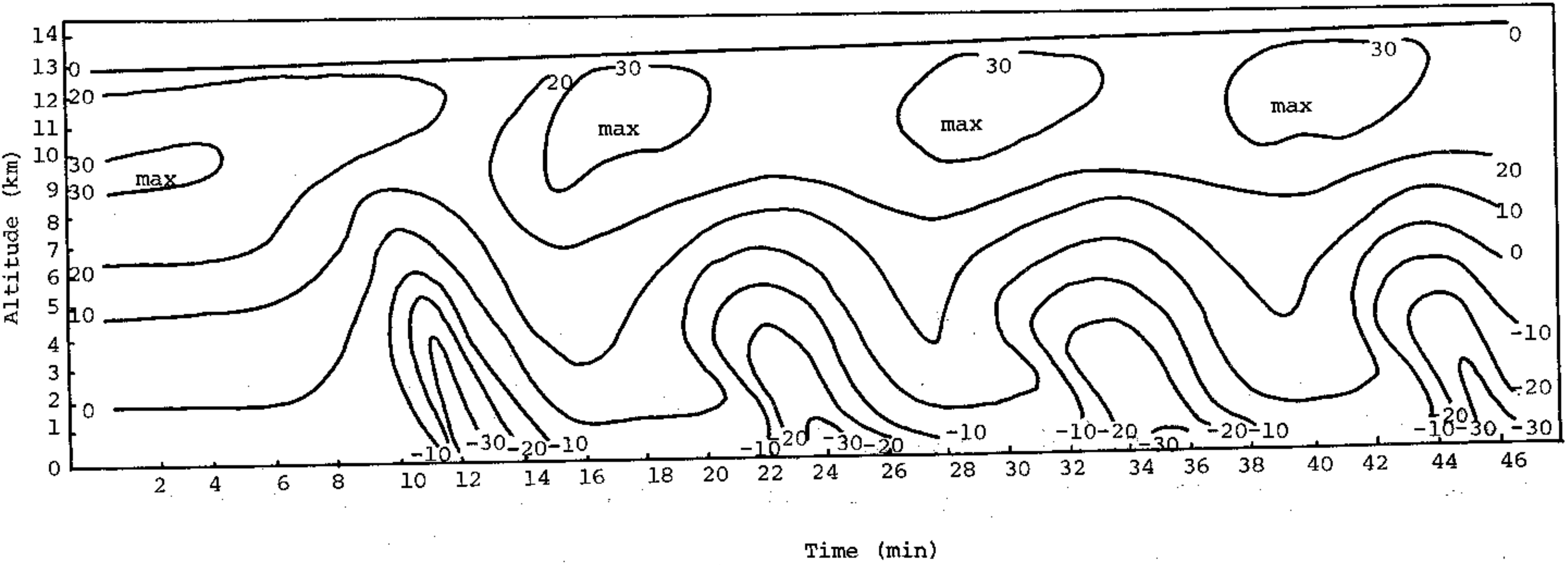

Fig. 9. Height-time cross-section of vertical velocity in a one-dimensional adiabatic model. Isopleths are labelled in units of m s^{-1}. Positive values denote updraft and negative values downdraft.

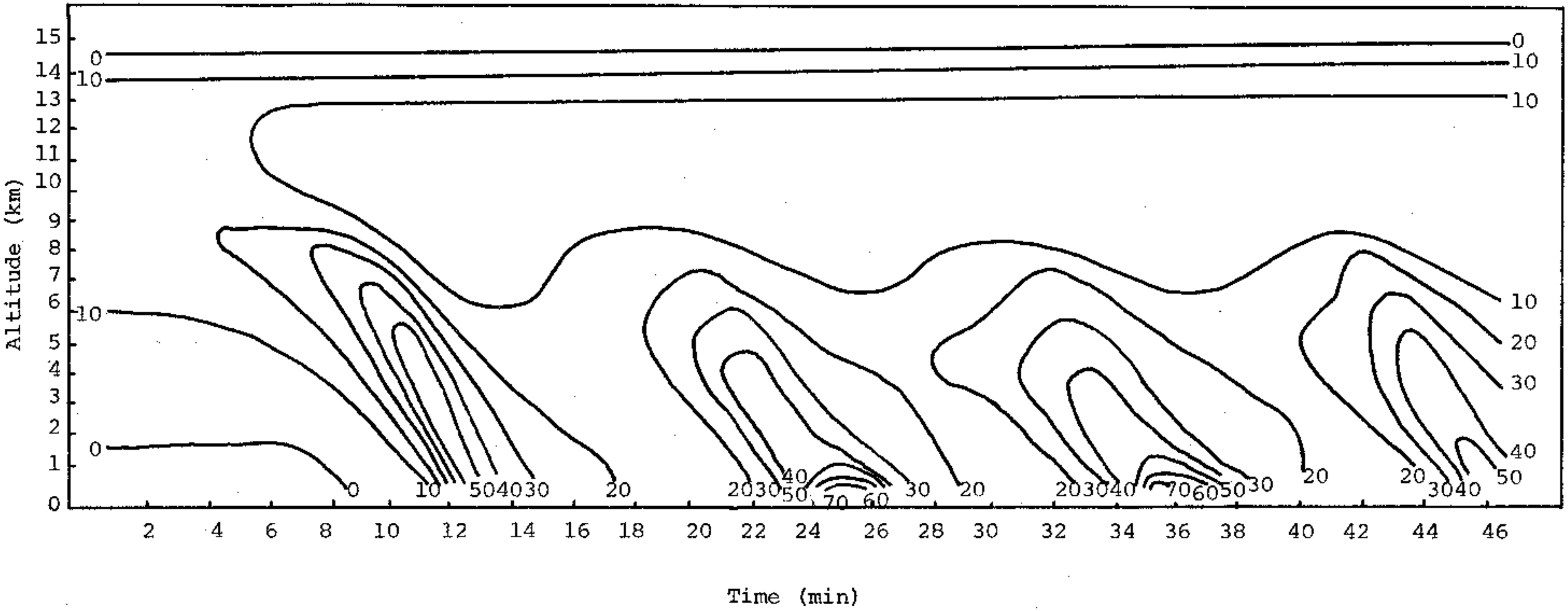

Fig. 10. Time-height cross-section of mixing ratio of the condensed phase (ξ). Isopleths are labelled in units of g kg $^{-1}$.

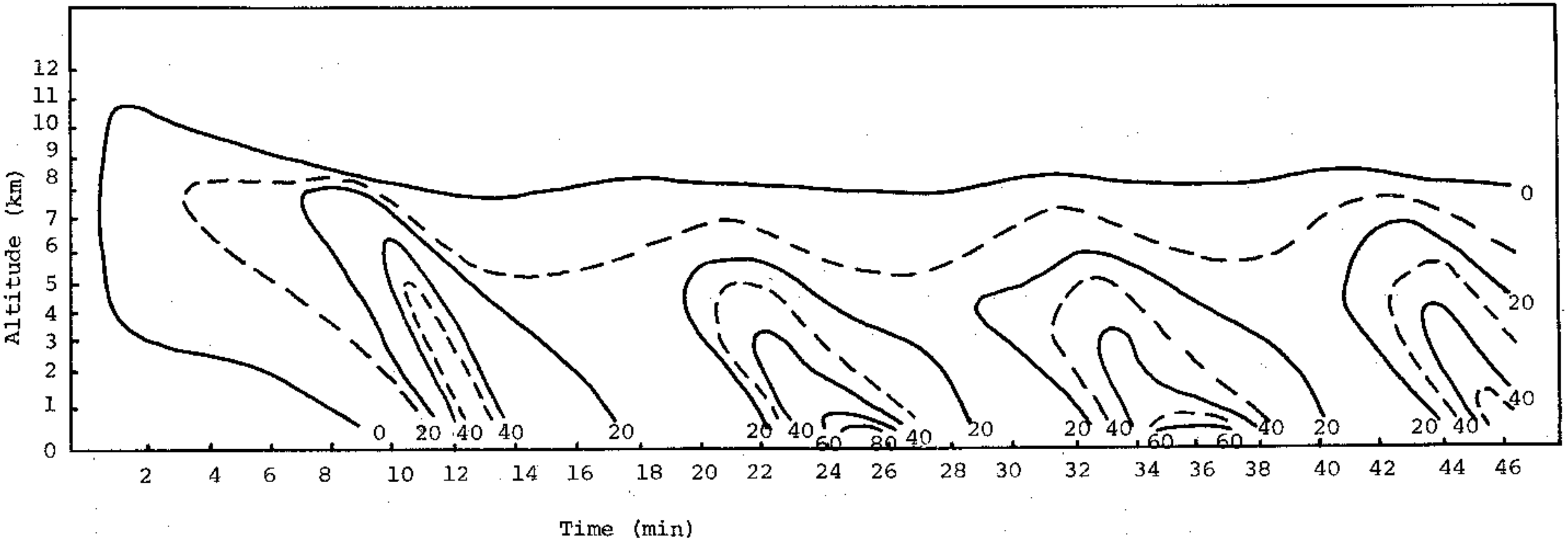

Fig. 11. Time-height cross-section of rainwater mixing ratio. Isopleths are labelled in g kg^{-1}.

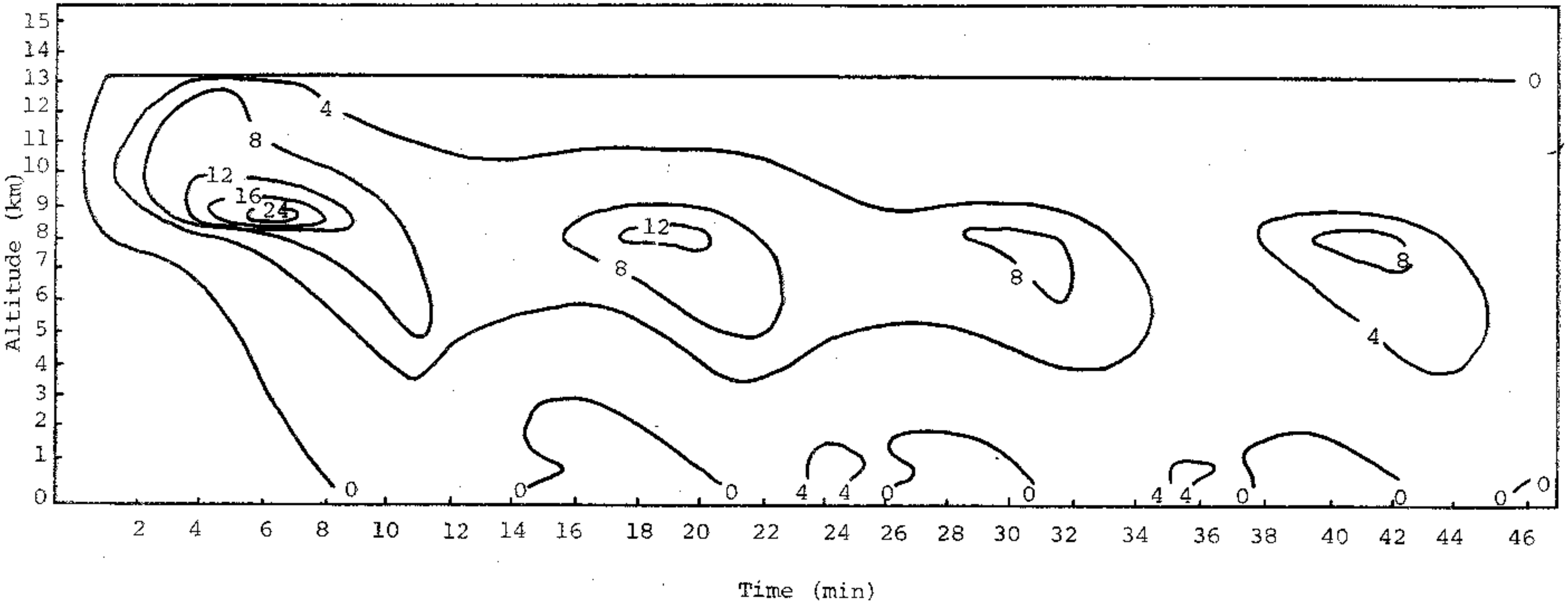

Fig. 12. Time-height cross-section of mixing ratio of hail, isopleths labelled in g kg^{-1}.

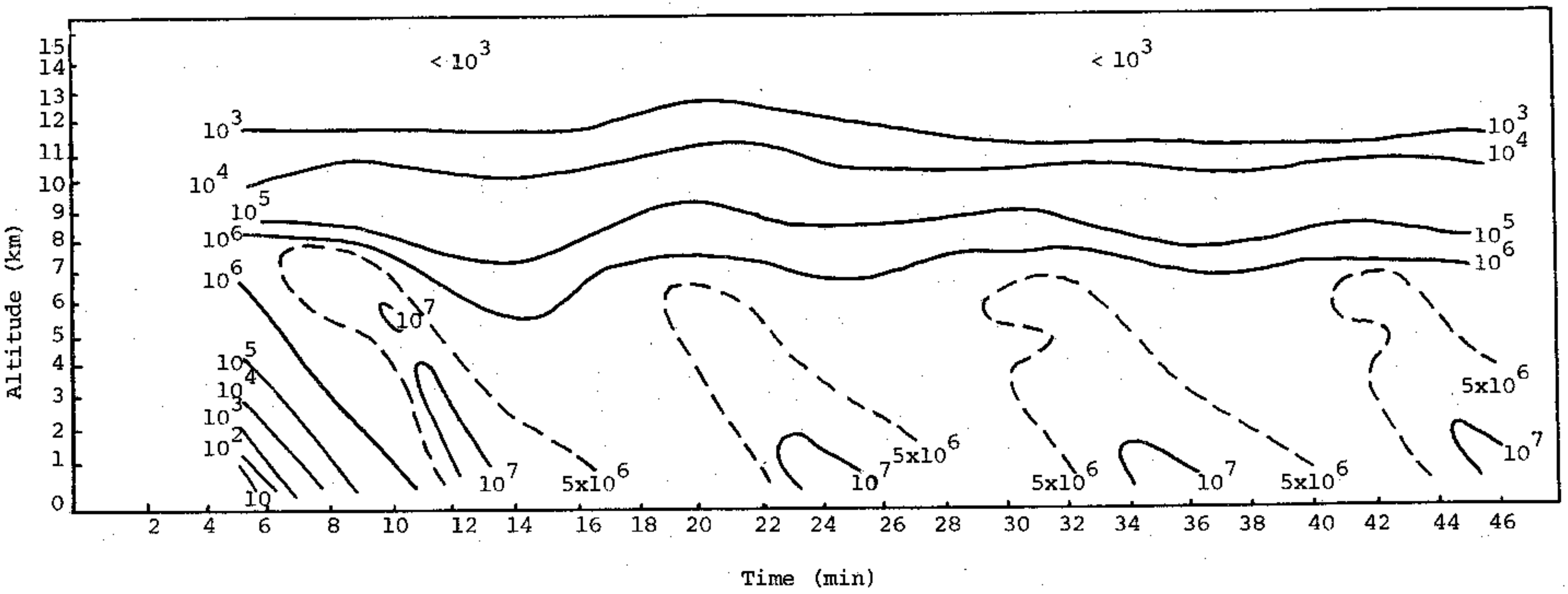

Fig. 13. Time-height cross-section of radar-reflectivity factor, isopleths labelled in $mm^6\ m^{-3}$.

near the time of occurrence of a severe-weather phenomenon, such as hail, funnel cloud, and/or tornado; and (2) those with which no severe weather could be associated. The second set of observations could relate to rain if there was a report to that effect. Since the usable rain reports for our purpose were only the daily ones, we adopted the following procedure. If on a given date there were, say, five radar observations and there was any report of rain over the circle of 40-mi radius (analysis area), we would treat it as five cases of radar echoes associated with the reported 24-hr amount of rainfall. On the other hand, severe-weather phenomena were classified into two parts, viz., hail, and tornado and funnel clouds. In the present data set hail and tornado-funnel cloud incidences were mutually exclusive, rendering simplicity to classification. The analysis described in this paragraph is shown in Table 20.

Table 20. Radar-Echo-Coverage vs. significant weather.

Significant Weather	Percentage of Analysis Area Covered by Radar Echoes						
	< 3%	3-6%	6-10%	10-15%	15-20%	>20%	Total
Hail	0	2	3	2	0	0	5
Tornadoes and Funnel Clouds	0	4	1	2	0	0	7
Rain only	80	47	17	16	4	1	165

An examination of Table 20 shows no relationship between the weather phenomena and the areas covered by the radar echoes, except that the rain-only cases predominantly have radar-echo coverages of small magnitude. The apparent relationship in the rain-only cases, however, may be misleading, as discussed below.

In order to find out if there was any relationship between the amount of rainfall and the percentage of analysis area covered by radar echoes (Radar Echo Coverage) the data were processed to reflect the fact that rainfall reports were sparse in space and time. So, for a calendar date the largest value of the radar-echo coverage and the maximum rainfall reported for all the reporting stations in the analysis area were tabulated. We thus obtained 28 cases, the analysis of which is shown in Table 21. This table tends to show that the smaller amounts of daily rainfall are related to smaller values of Radar-Echo Coverage. However, it is also clear that both smaller Radar-Echo Coverages and smaller rainfall amounts occur with relatively higher frequencies so that an association indicated in Table 21 may be fictitious and misleading. Another source of difficulty may arise from the fact that the shower from a radar cloud of small areal extent has a greater probability of missing a raingauge.

In conclusion, it needs to be stated that the data lack both in quality and quantity to arrive at any firm conclusion. For arriving at statistical conclusions the observational procedure with respect to radar as well as rain and hail has to be laid out with greater care than evidenced in the present set of data.

Table 21. Radar-Echo Coverage vs. rainfall.

Max. 24 hour rainfall (inches)	Daily Max. Radar-echo Coverage ≤3%	3-6%	6-10%	10-15%	>15%	Total
<.25	4	1	1	3	2	11
.25-.49	2	2	0	1	0	5
.50-.99	1	2	3	0	0	6
1.00-1.99	1	1	1	0	0	3
≥2.00	1	0	0	0	2	3
Total	9	6	5	4	4	28

CHAPTER VI. CONCLUSIONS AND RECOMMENDATIONS

There are several limitations of this study which must be understood and considered when interpreting the results. These are:

(1) The ASCS data reflect total crop losses due to weather, while the loss due to hail alone is unknown.

(2) The official rain gages are sparse and inadequate for determining the desired information on the areal distribution and amount of rainfall. It is possible that a limited area could be affected by seeding (increase or decrease in rainfall) and not be reflected in the precipitation measurements.

(3) There were no hail data used in the analysis of hail prior to the seeding period.

A limitation associated with weather damage data from the USDA must be recognized. The weather related losses are established by the County ASCS office. Generally the loss (or approved adjusted yield) relies to a large degree on the producer's established average yield. In favor of these data, major weather factors are listed that contributed to the producers yield being less than his average over time.

A. CONCLUSIONS

In general analyses of the data disclose that the period 1970-73, on the whole, received less rainfall than the preceding 4-yr period. However, this reduction occurred in both seeded and non-seeded regions. No significant difference in the observed rainfall between the two regions was detectable. The findings of this study tend to suggest that weather-modification attempts had no significant effect on the observed rainfall distribution. Rather, the reduction in rainfall during the seeded years appears to be another of the random fluctuations that characterize the long-term climatology of the area. A diminution in rainfall most likely would have occurred anyway, even if cloud seeding had not been done.

The statistical analyses of the hail and cotton-loss data did not indicate a significant effect on hail damage due to cloud seeding. This does not prove that there is no effect from the seeding program, but that, based on the available data, no effect could be discerned. This finding is based primarily upon data of cotton damage and loss attributable to hail. An analysis of variance of crop insurance and acreage data revealed that only the variation between years is a significant factor. There was no indication of significantly different losses due to the seeding effect or of the losses encountered between different counties within the seeded group.

Since the analysis did not indicate a statistically significant reduction in hail damages due to the cloud seeding, there is no basis for establishing any economic returns as a result of the program.

Severe weather phenomena were found to be independent of radar-echo coverage. The lack of data prevented any firm conclusions about the relationship between radar-echo coverages and smaller rainfall amounts.

B. RECOMMENDATIONS

Further study along the following lines is suggested:

(1) Additional rainfall, rain-day, and hail data are needed to depict a more accurate description of the actual distribution of rainfall and hail occurrences throughout the study region.

(2) An analysis of data of stations downwind from the target area could ascertain the effects of seeding on rainfall and hailstorm patterns along distances of 100-200 km.

(3) A shift in seeding seasons would permit a determination of the effects of cloud seeding on precipitation of nonconvective origin.

(4) A better understanding is needed of the effects of areal variability of point rainfall and hail data and how the areal variability of rainfall and hail occurrences affects the rainfall statistics.

(5) A more exact observational procedure with respect to radar data as well as rainfall and hail data is needed to ascertain a statistically significant relationship between radar-echo coverage and severe weather phenomena.

It is hoped that this study will serve as a guide for further research into an appraisal of how present-day weather-modification activities are affecting rainfall and hailstorm patterns.

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APPENDIX A

A list of the selected stations with their location, elevation (m), and number of years of record.

Station Number	Name	N Lat.	W Long.	Elevation (m)	Years of Record
0012	Abernathy	30°50'	101°51'	1027	26
1128	Brownfield No. 2	33°11'	102°16'	1006	34
2121	Crosbyton	33°40'	101°14'	921	34
2463	Dimmitt 6 E	34°33'	102°13'	1161	34
2464	Dimmitt	34°33'	102°19'	1175	15
3214	Floydada	33°59'	101°20'	969	21
3215	Floydada 9 SE	33°52'	101°15'	953	23
3368	Friona	34°38'	102°43'	1222	11
3972	Hart	34°23'	102°07'	1113	19
5183	Levelland	33°34'	102°23'	1082	26
5265	Littlefield No. 2	33°54'	102°21'	1067	24*
5363	Lorenzo	33°40'	101°32'	966	20
5411	Lubbock WSO AP	33°39'	101°49'	992	34
6074	Morton	33°43'	102°45'	1143	26
6135	Muleshoe No. 1	34°14'	102°43'	1152	34
6644	Olton	34°11'	102°08'	1100	10
7079	Plainview	34°11'	101°42'	1027	34
7361	Quitaque	34°22'	101°03'	783	8

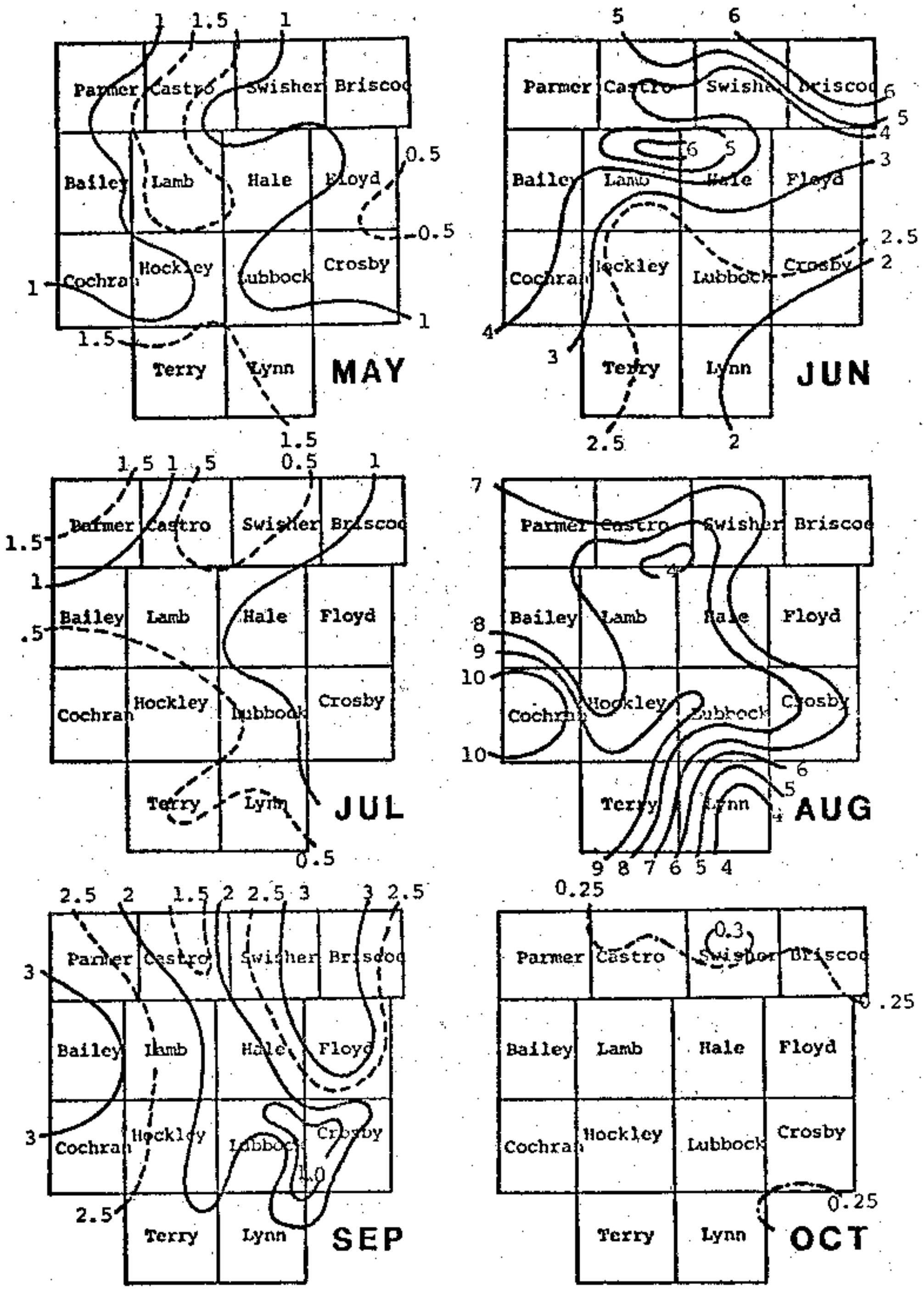
Station Number	Name	N Lat.	W Long.	Elevation (m)	Years of Record
8323	Silverton	34°29'	101°19'	1000	25
8373	Slaton 5 SE	33°22'	101°36'	930	24
8818	Tahoka	33°10'	101°49'	951	21
9175	Tulia	34°32'	101°46'	1061	33**

* Data for 1963 were unavailable.

** Data for 1948 were unavailable.

APPENDIX B

Maps showing patterns of observed monthly rainfall based on station totals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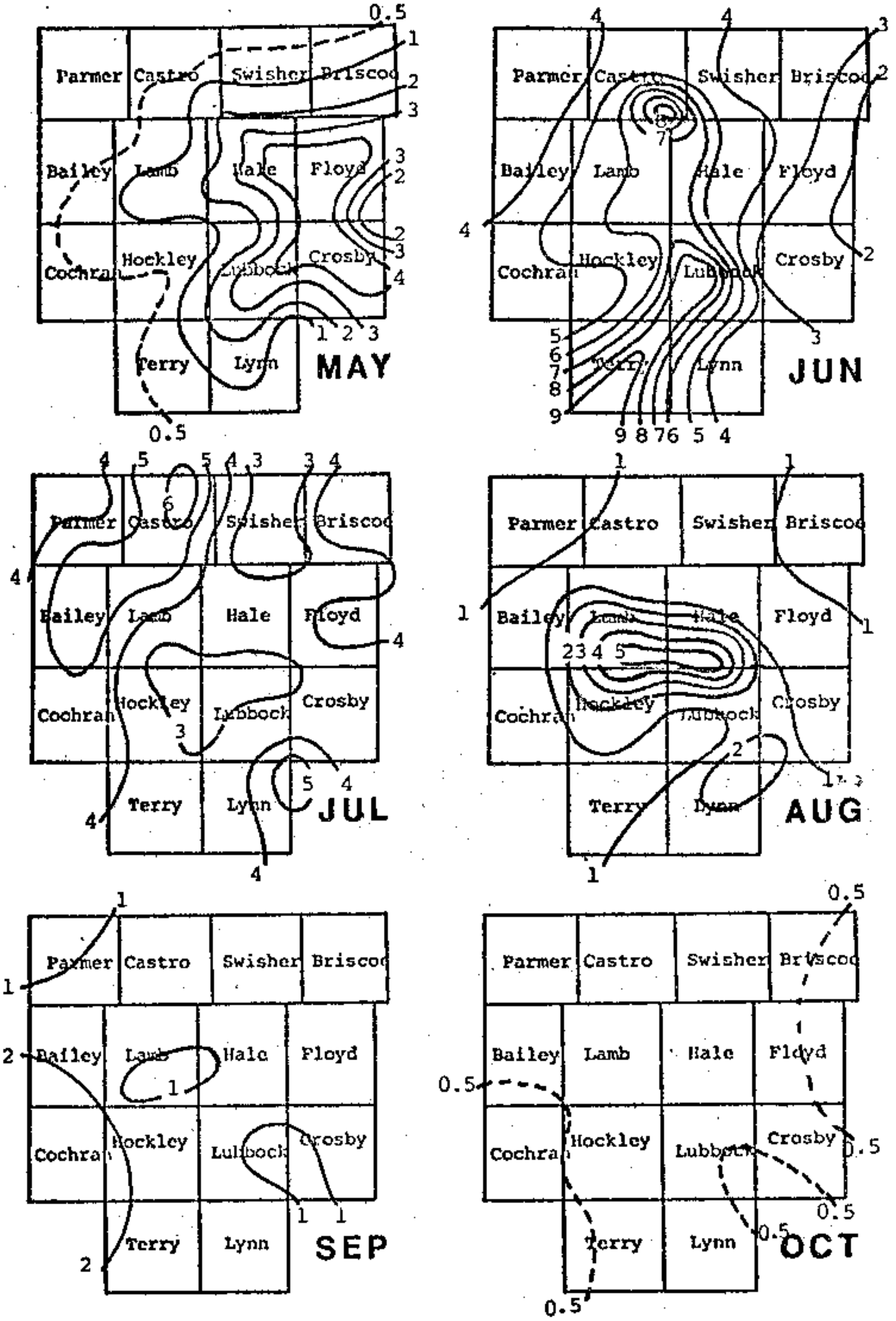
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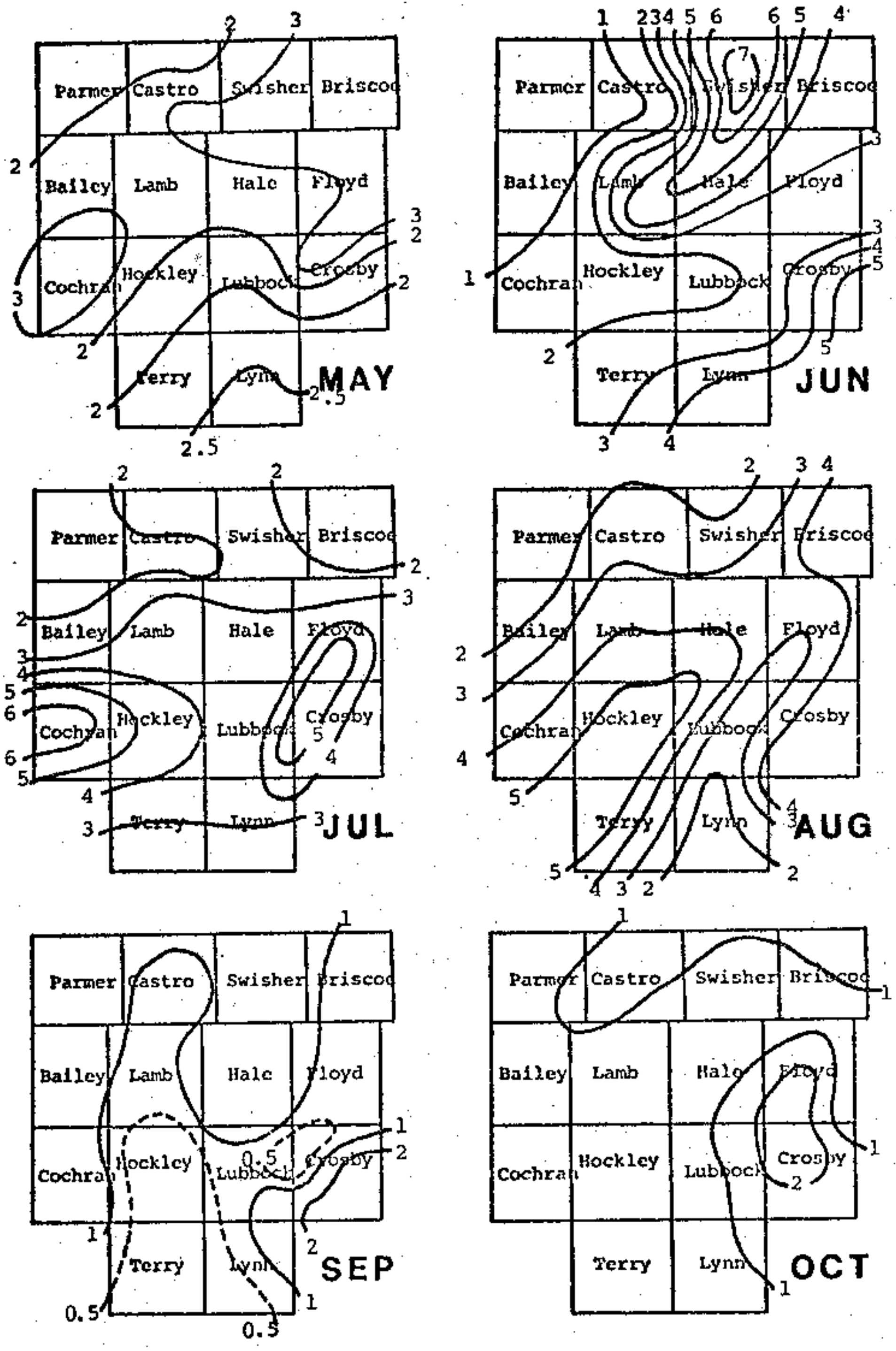
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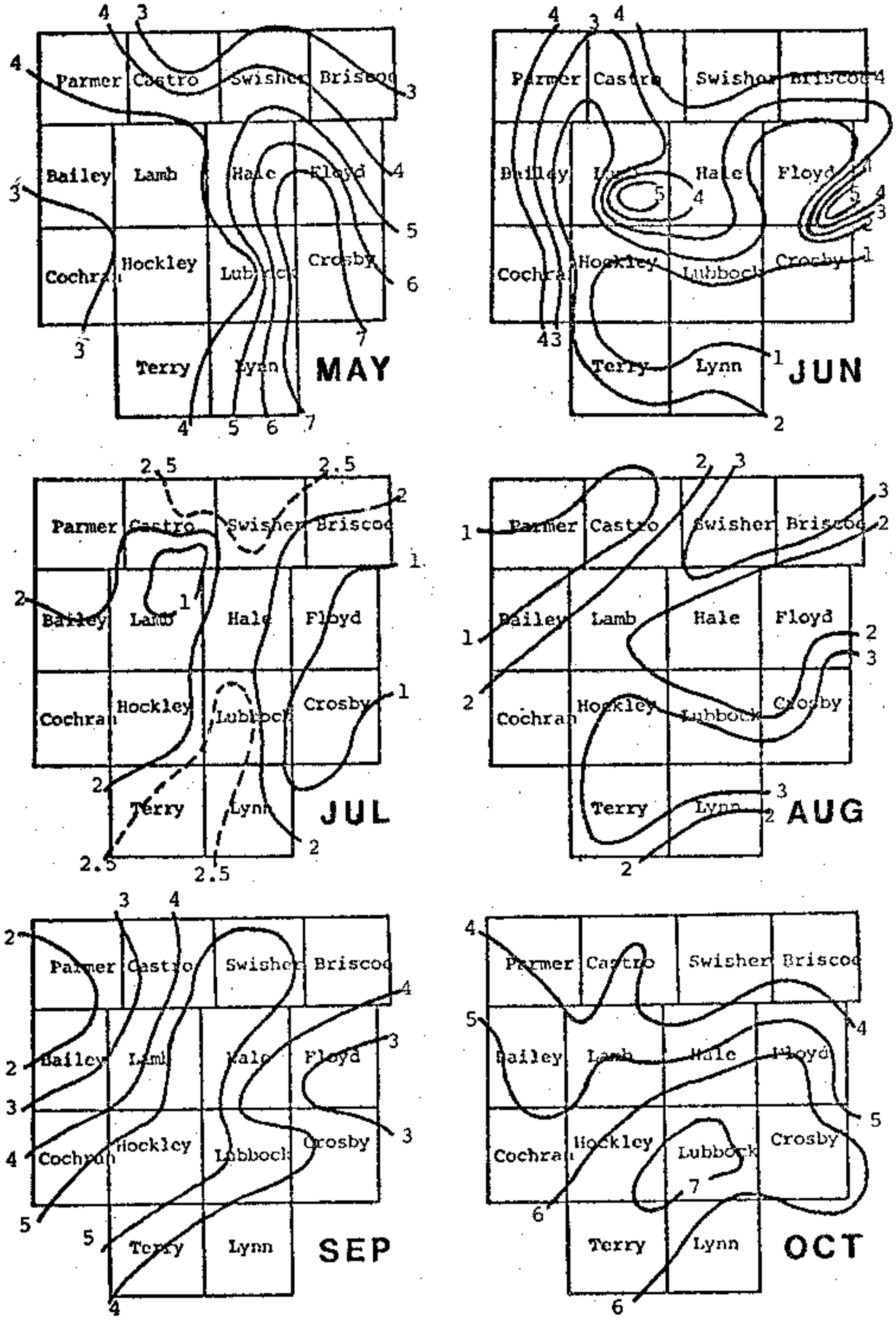
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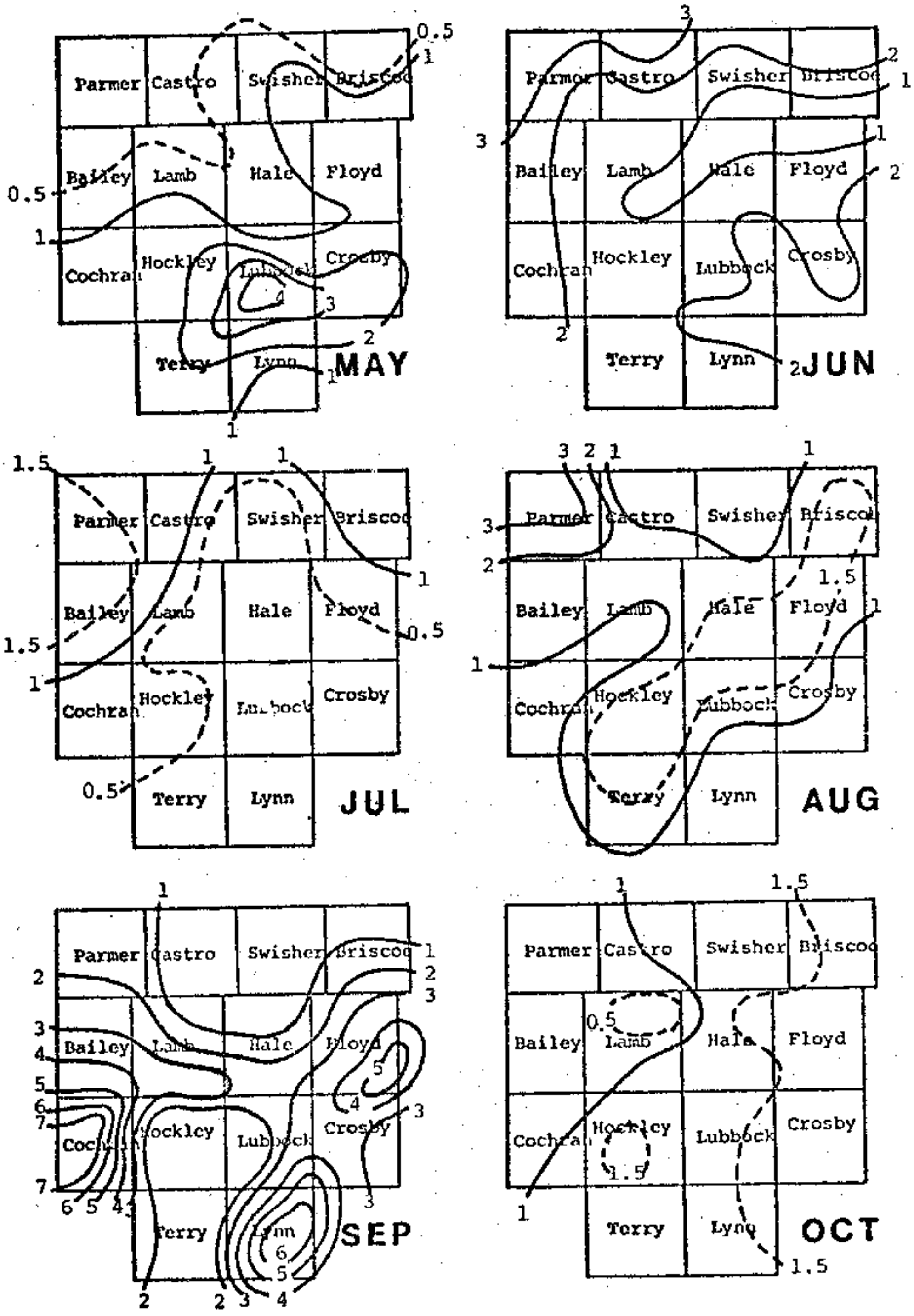
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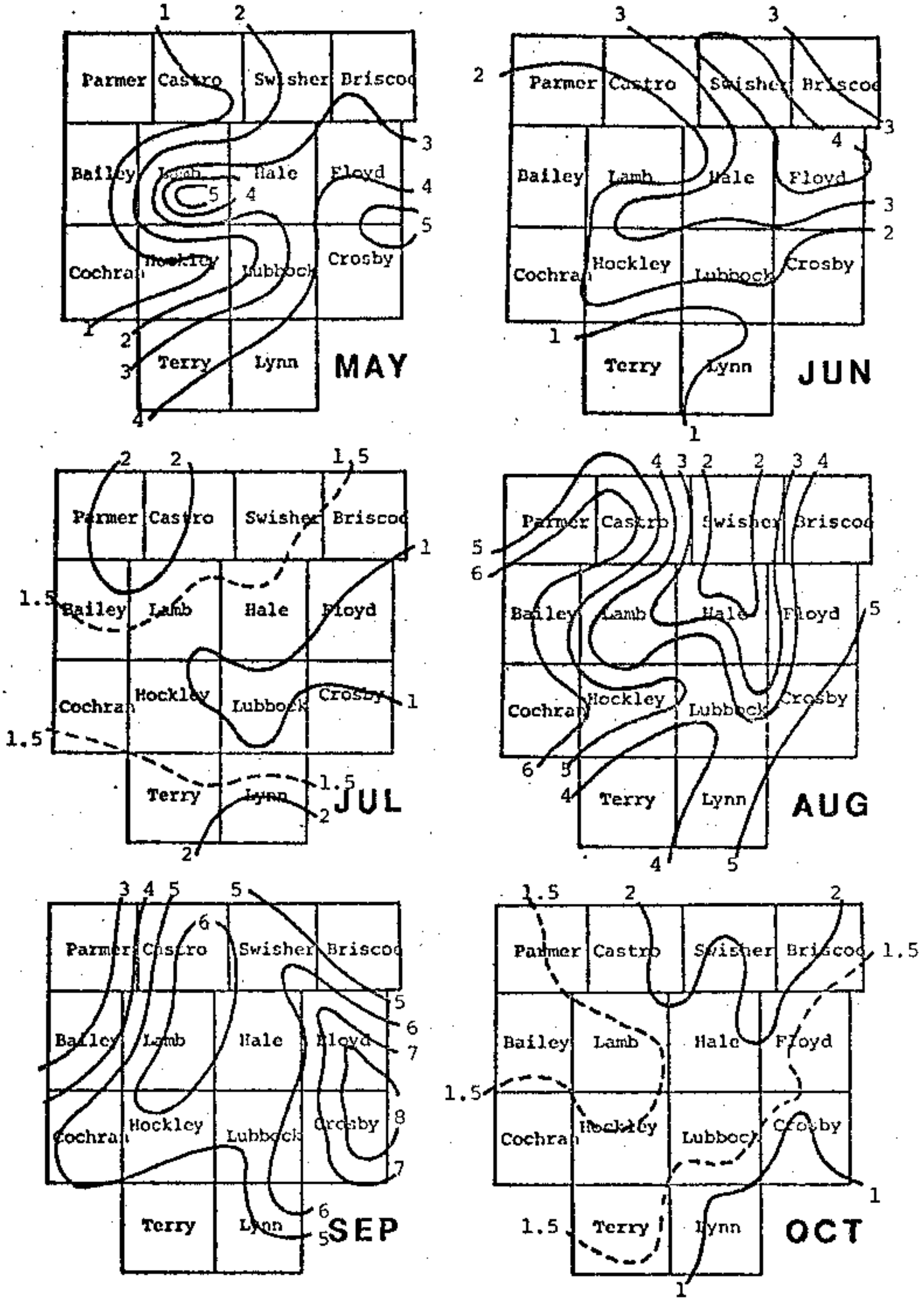
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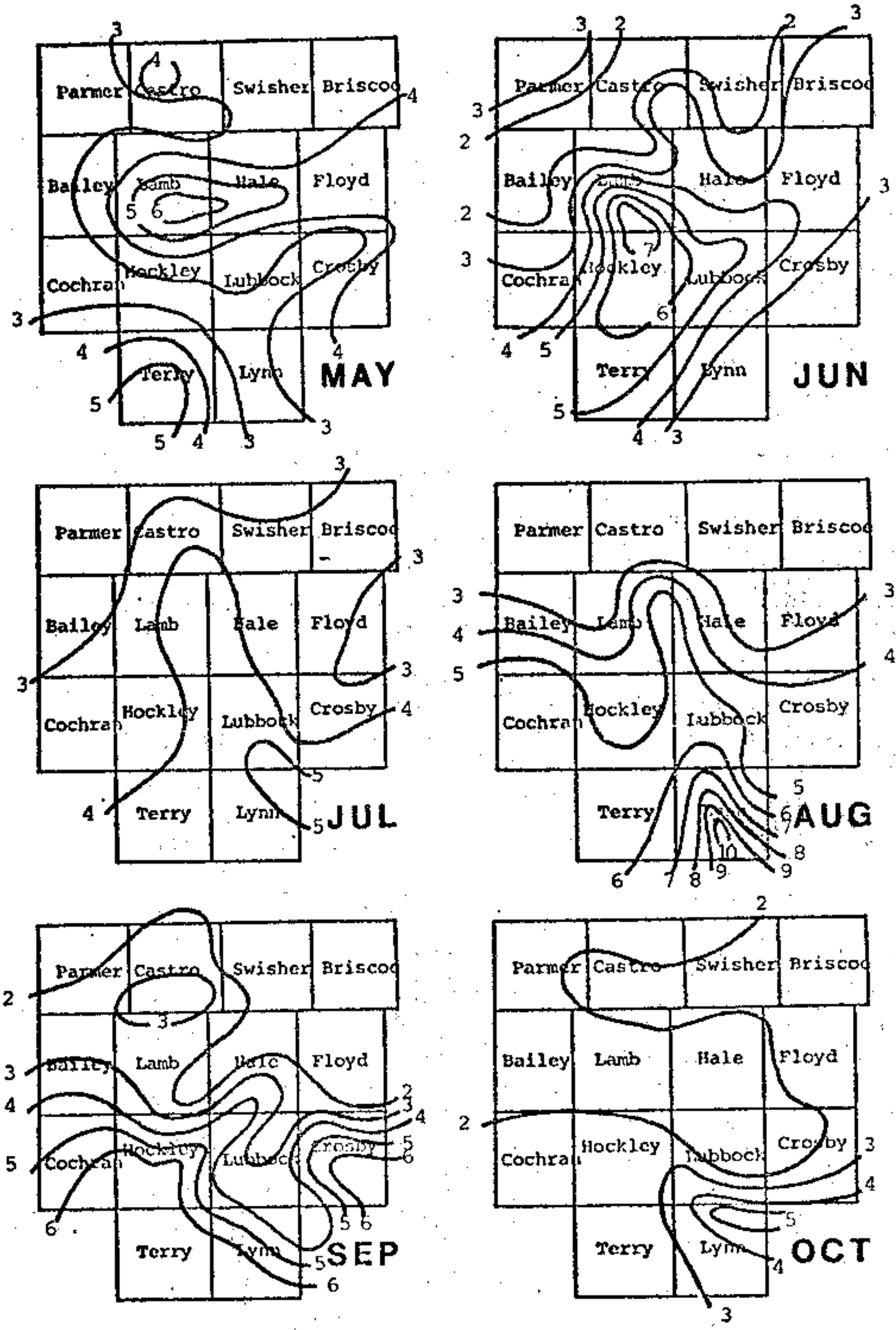
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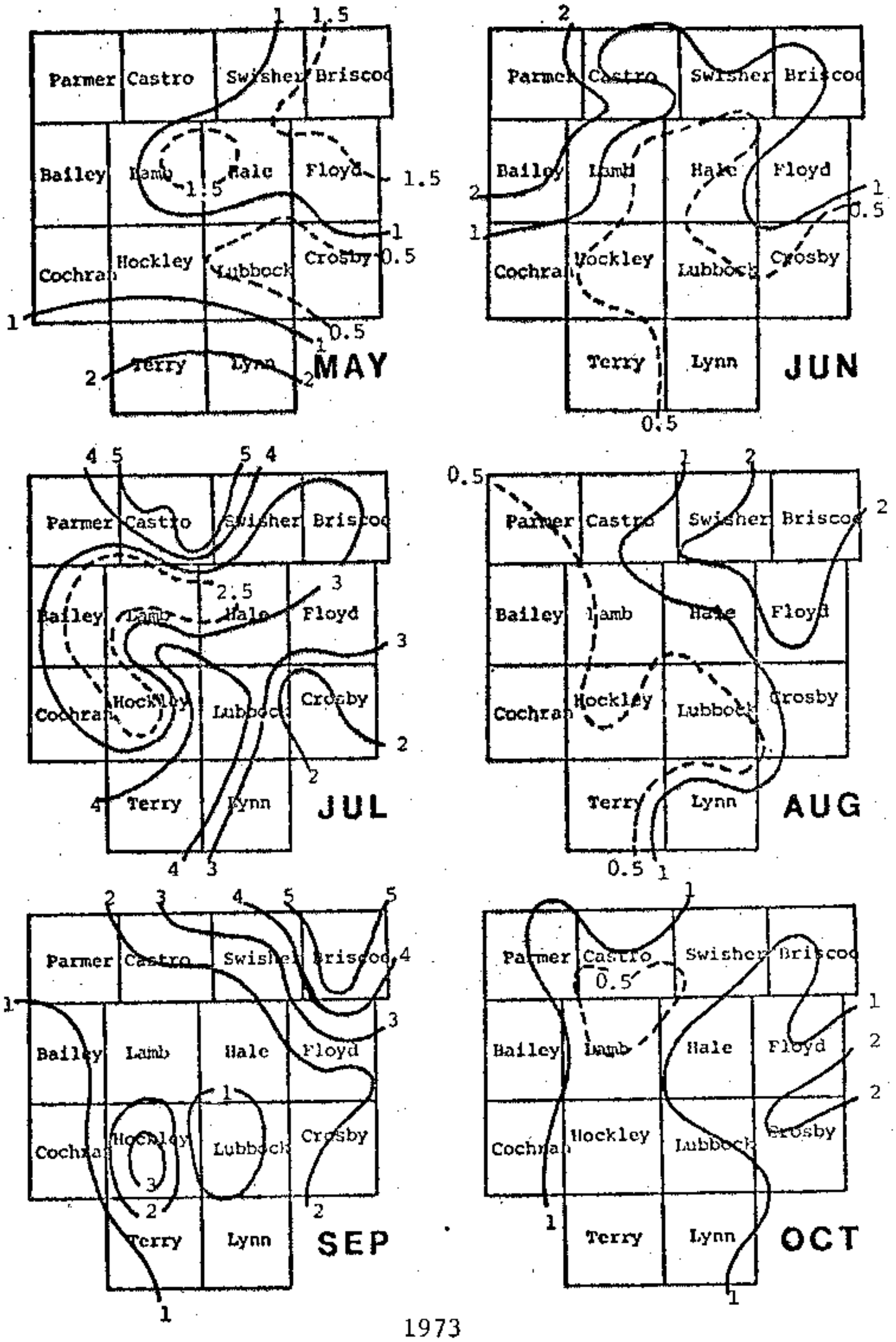
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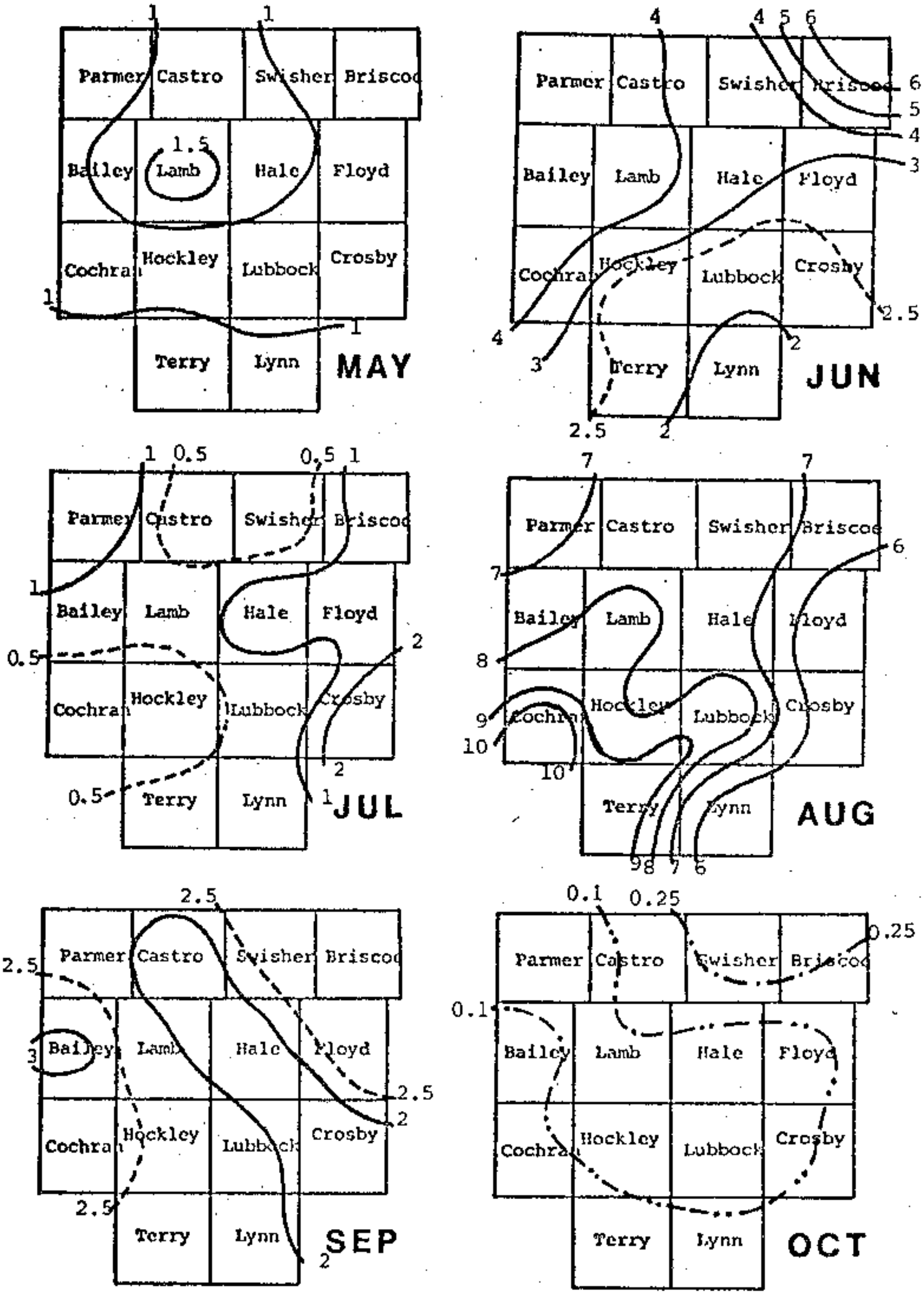
APPENDIX C

Maps showing patterns of observed monthly rainfall based on county averages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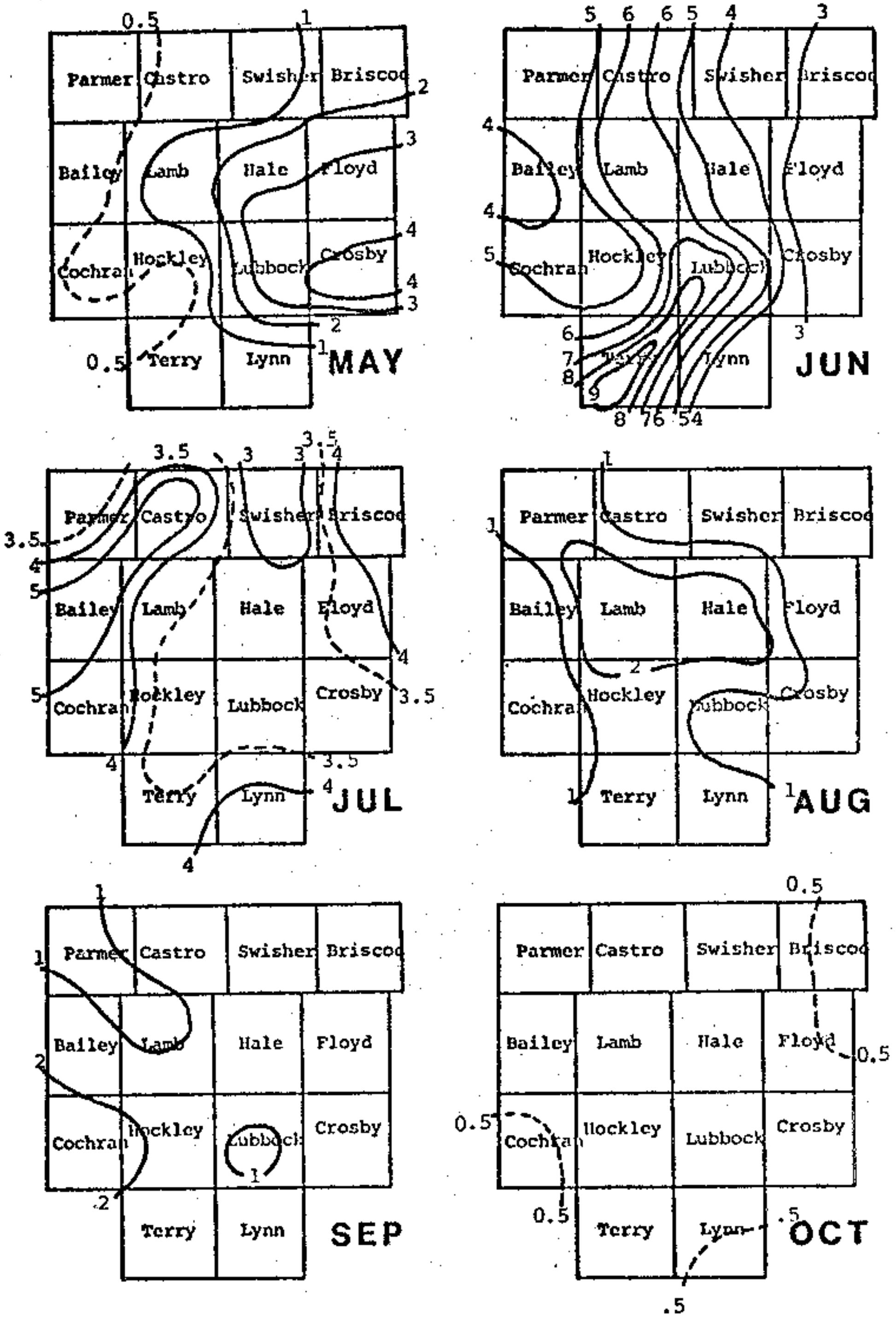
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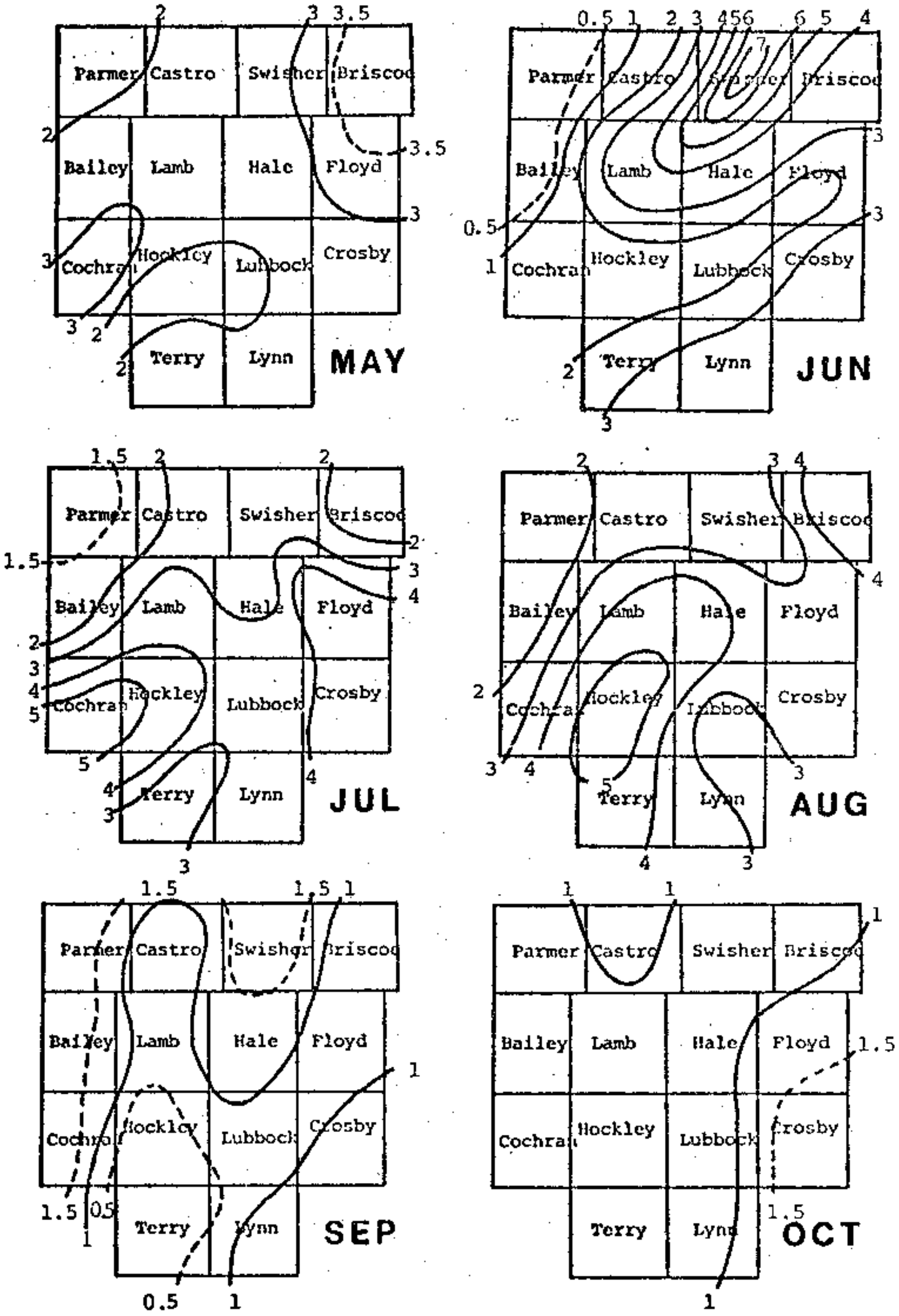
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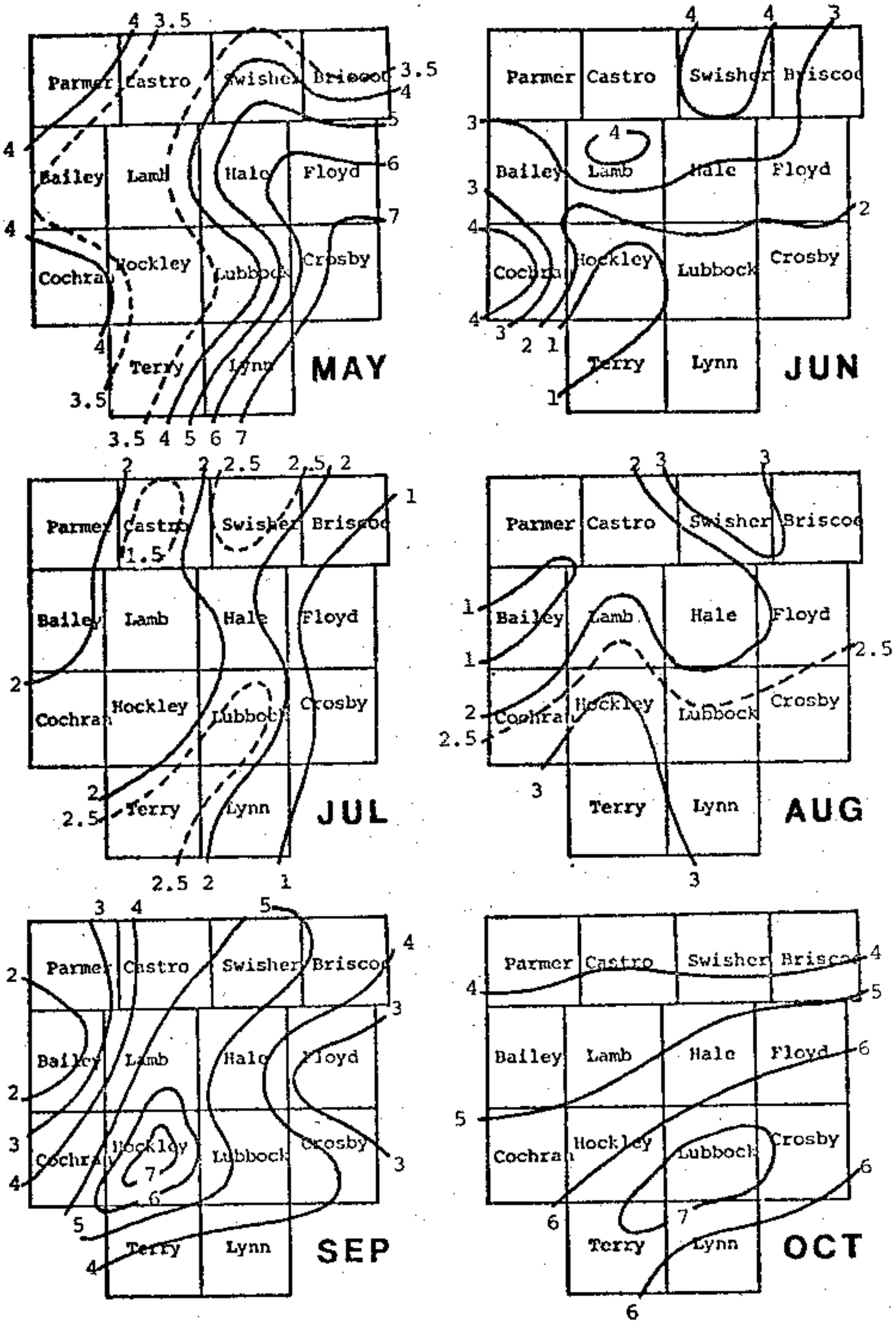
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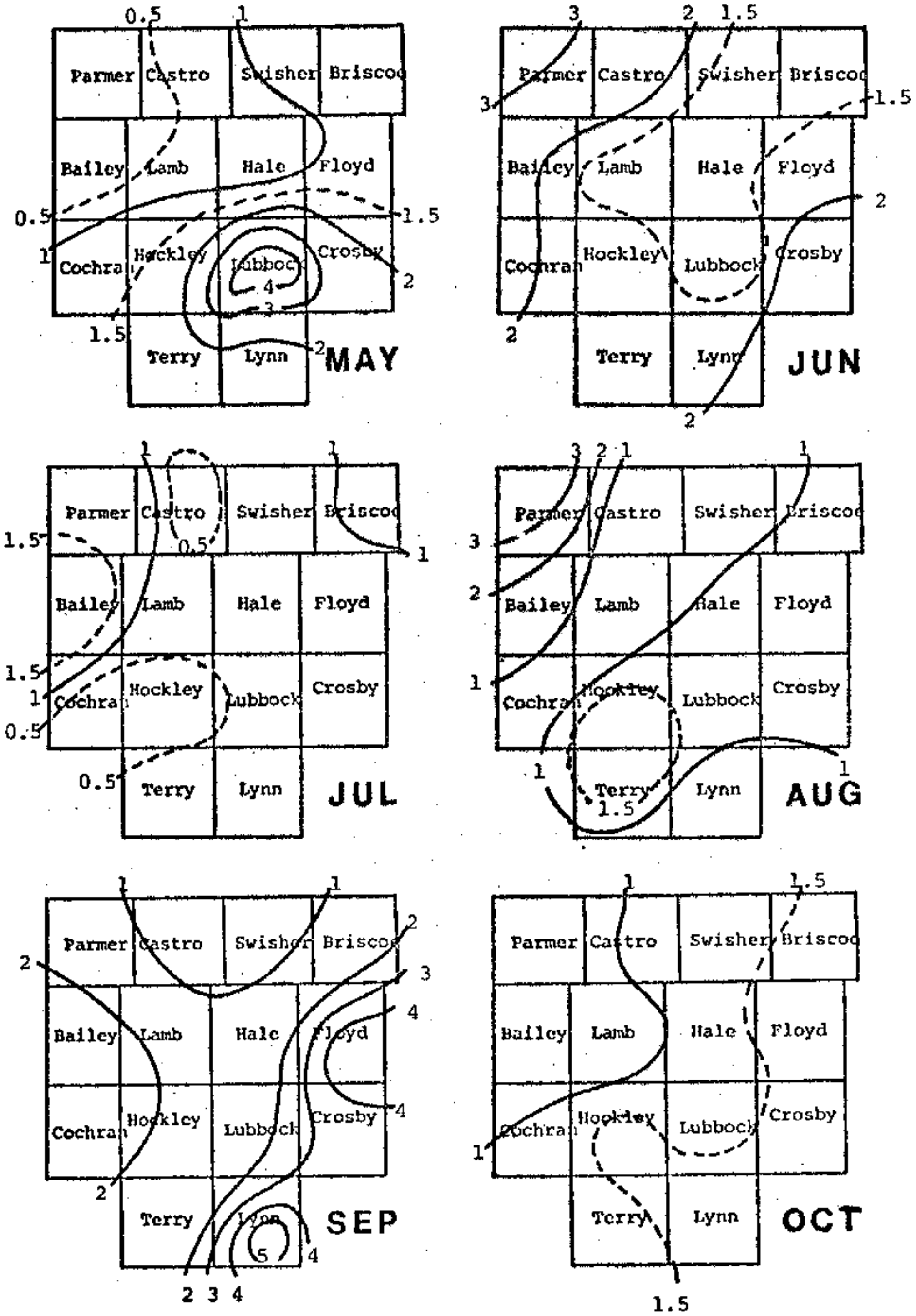
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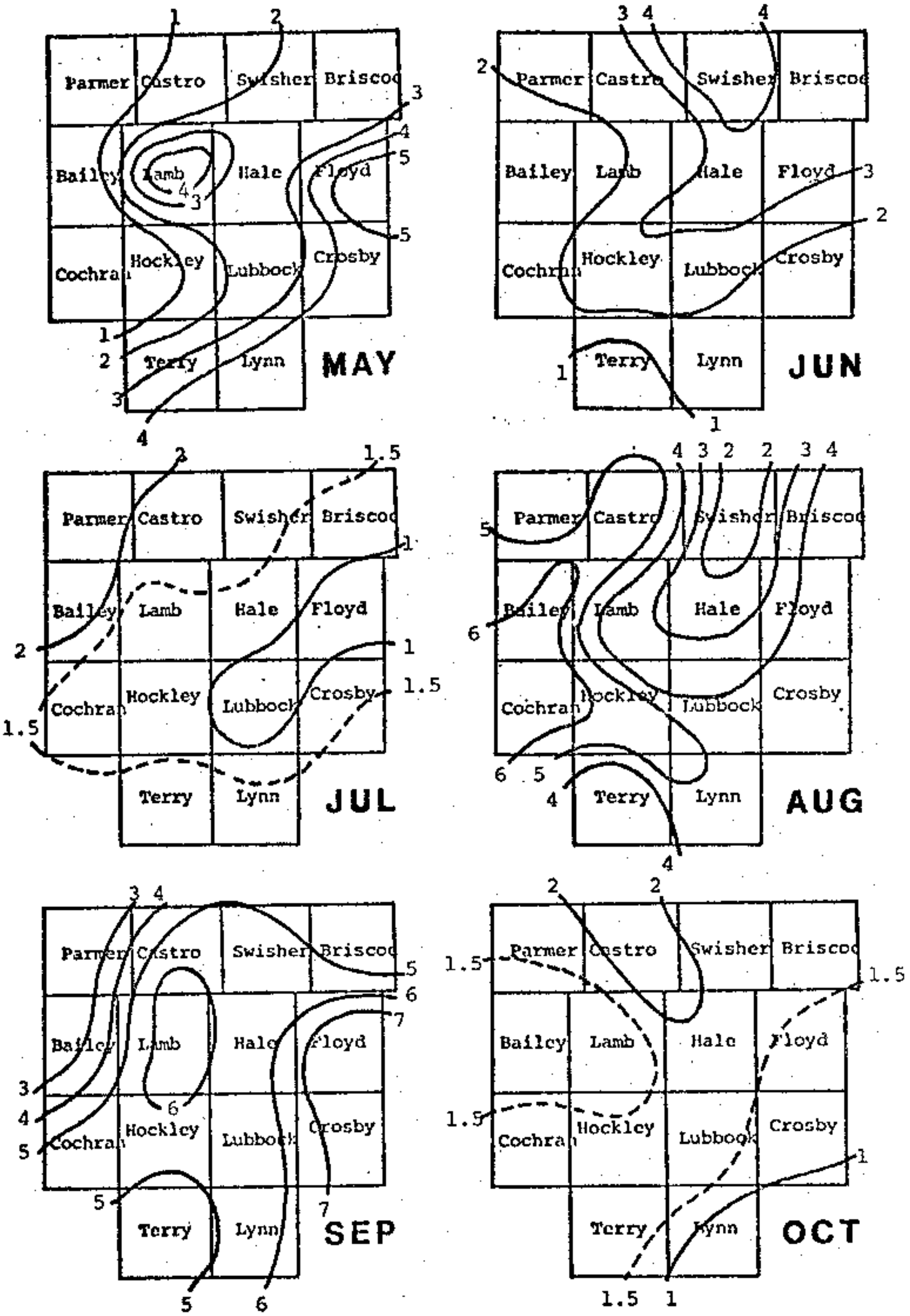
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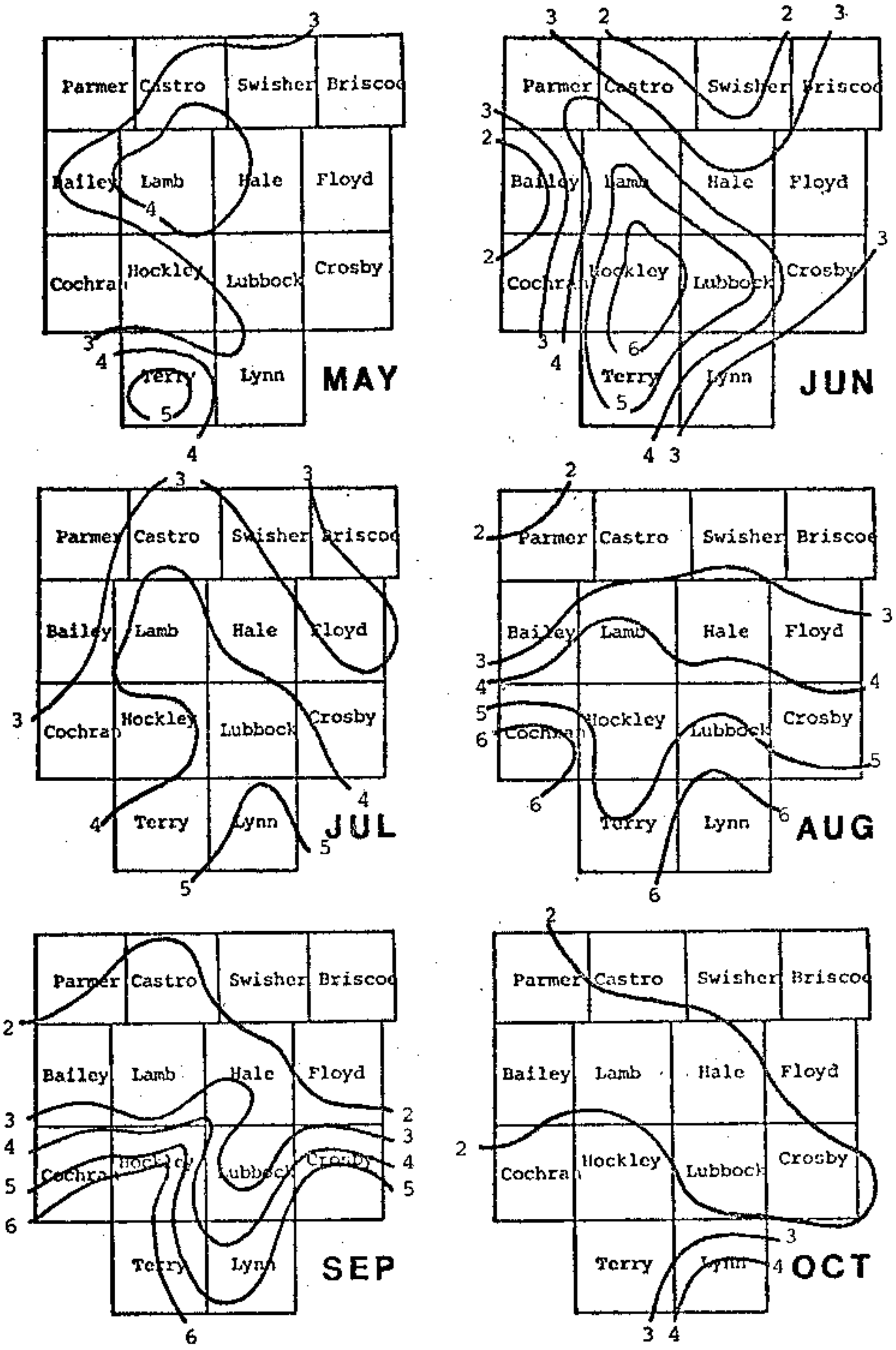
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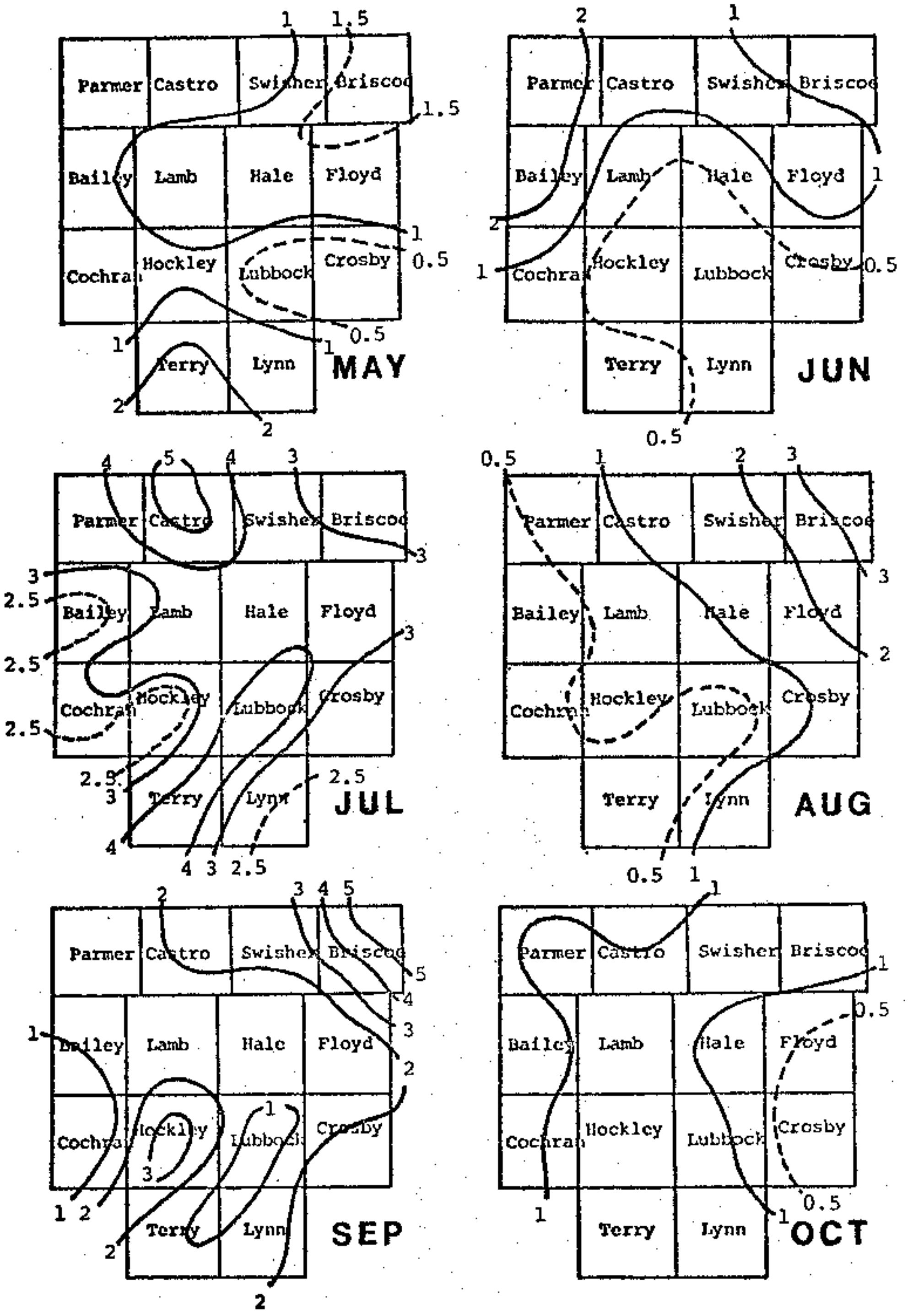
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APPENDIX D

Glossary of Statistical Terms

It cannot be too strongly emphasized that for a real understanding of statistical techniques (particularly the quantitative and numerical aspects of statistical techniques) reference must be made to the basic textbook literature e.g., to a study of the books by Ostle and/or Draper and Smith listed in the references.

However, in order to convey the general ideas of the concepts employed in such statistical analysis, we are giving below a brief glossary of the concepts employed in the present report.

1. Analysis of variance (ANOVA) - The analysis of the total variability of a set of data (measured by their total sum of squares) into components which can be attributed to different sources of variation. A table which lists the various sources of variation together with the corresponding degrees of freedom, sums of squares, mean squares (sometimes also expected mean squares), and values of F, is called an analysis of variance table. (Sometimes abbreviated ANOVA). The terms also refer to the totality of statistical techniques based on this kind of analysis. See also One-Way Analysis of Varieance; Two-Way Analysis of Variance.

2. Error Variance - The variance of a random (or chance) component of a model; the term is used mainly in the presence of other sources of variation, as for example in regression analysis or in analysis of variance. It is referred to as X^2 in the descriptions of model equations.

3. Error Mean Square - In analysis of variance, the error sum of squares divided by its degrees of freedom; it provides an estimate of the (supposedly) common error variance of the populations in all components due to different sources of variation.

4. Valid Error - An error mean square is regarded as a "Valid Error to test the significance of a mean squares due to another source of variation (such as the effect of seeding) if the latter mean square has an expected value equal to the "valid error mean square" in case there is no effect of seeding (dummy source of variation).

5. Chi-square Statistic - A statistics which is given by a sum of terms where each term is the quotient of the squared difference between an observed frequency and an expected frequency divided by the expected frequency.

6. Chi-square Test - A particular form of this test will test the differences between two frequency distributions (histograms) by computing a sum of squared differences between the percentage frequencies of the two distributions (the Chi-squared statistic) and assessing whether the magnitude of these statistics indicates differences larger than those which could have occurred by chance.

Glossary of Statistical Terms (Continued)

7. F-Test - A statistical test which gauges the magnitude of the component of variation due to a particular source against the component due to prior experimental error by forming the ratio of the two components (mean squares) and gauging this ratio against the standard F-test tables.

8. Regression - The relationship between the (conditional) mean of a random variable and one or more independent variables; a mathematical equation expressing this kind of relationship is called a regression equation. When the regression equation is a linear equation the regression is also referred to as linear; when the regression equation represents some other kind of curve or surface the regression is referred to as curvilinear. The term "regression" is due to Francis Galton, who employed it first in connection with a study of the heights of fathers and sons, observing a regression (or turning back) from the heights of sons to the heights of their fathers.

9. Significance Test - In hypothesis testing, a test which provides a criterion for deciding whether a difference between theory and practice (a difference between observations and corresponding expectations, or a difference between an observed value of a statistics and an assumed value of a parameter) can reasonably be attributed to chance. If the difference is so small that it can be attributed to chance, one has the option of accepting the hypothesis on which the theoretical value (or values) was based, or of reserving judgment (when feasible) by merely stating that the data do not permit the rejection of the null hypothesis.

10. Histogram - A graph of a frequency distribution obtained by drawing rectangles whose bases coincide with the class intervals and whose areas are proportional to the class frequencies. In a histogram representing a distribution with equal classes, the heights of the rectangles are also proportional to the class frequencies.

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