Article Title:

Efficacy analysis of cloud seeding program in Kansas agriculture

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Abstract: Hailstorms cause significant economic losses worldwide, and the central United States is particularly vulnerable due to increasing hailstone size linked to climate change. Cloud seeding, a weather modification technology, has been widely adopted for hail suppression in over 50 countries since the 1970s. While existing research predominantly focuses on hailstone size and frequency, its effects on crop damage and productivity remain understudied. This study evaluates the effectiveness of cloud seeding in Kansas using county-level data from 2002 to 2020, considering a broader set of measurements: hail size, hail frequency, crop damage, crop yields, and potential downwind effects. The findings reveal that cloud seeding reduces hailstone size in target areas but does not significantly decrease crop damage from hail or drought. Conversely, it is associated with increased flooding damage to crops. Additionally, cloud seeding enhances corn productivity in target areas but negatively affects sorghum productivity in downwind regions, suggesting potential spillover effects. A cost-benefit analysis indicates that while the overall net present value of the Kansas cloud seeding program is positive, some downwind counties experience negative net benefits. These findings challenge the conventional evaluation metrics of cloud seeding programs and underscore the need for a holistic approach to assess their effectiveness. Policymakers should consider these insights to improve program design, mitigate adverse effects, and enhance technology management. This study contributes to understanding the complexities of weather modification programs and provides evidence to guide future policy decisions on hail suppression.

Keywords: cloud seeding, weather modification, hail suppression, crop damage, spillover effects, downwind effects, cost-benefit analysis

I. Introduction

Hailstorms cause tremendous economic losses in the United States (US) and across the globe. From 2003 to 2023, severe hailstorms caused $35.8 billion in losses in the US (NOAA, 2024)[1]. Moreover, hailstone size may increase in the central US and could potentially cause more damage in the future, according to meteorological simulations (Fan et al., 2022).

To mitigate hail damage, more than 50 countries around the globe have adopted weather modification programs, more specifically, cloud seeding, for hail suppression purposes since the 1970s, including the US, Russia, France, Argentina, etc.[2] The microphysical process of hail formation is extensively discussed in the literature (Lamb and Verlinde, 2011; Allen et al., 2020; see section II for more details). The main idea of cloud seeding for hail risk reduction is to launch chemical particles into clouds, thereby reducing the frequency and magnitude of hailstones (Knight, 1977).

Most existing research on the effectiveness of cloud seeding programs evaluates factors such as the size and volume of hailstones, the frequency of hail events, and the distribution of hailstone sizes over a certain period (Bergant, 2011; Changnon, 1971; Dessens et al., 2016; Gavrilov et al., 2013; Rivera et al., 2020; Spiridonov et al., 2015). Among these studies, the intensity of hail is often measured by the size of the hailstones, as smaller hailstones, which have less kinetic energy, are associated with less damage to crops, livestock, property, and even humans (Pirani et al., 2023; Púčik et al., 2019).

However, the relationship between the size of hailstones, frequency of hail events, and crop damage is not yet clear. In the literature, there are relatively few studies that examine the effect of cloud seeding hail suppression in reducing crop loss, but more studies on direct property damage (Allen et al., 2020; Changnon & Changnon, 2000; Childs et al., 2020). Childes et al. (2020) conducted interviews with farmers, revealing that most farmers worried about small-size large-volume hailstones more than large-size hailstones. Also,

[1]This number represents the costs attributed solely to hailstorms, although instances of tornado outbreaks, high winds, and hailstorms often occur concurrently. Furthermore, disaster costs in NOAA reports encompass damages to residential and commercial properties (including buildings, vehicles, and boats), infrastructure (such as roads, bridges, and electrical facilities), agricultural assets (including crops, livestock, and timber), as well as losses related to business interruptions.
[2] See World Meteorological Organization: https://public-old.wmo.int/en/resources/bulletin/seeding-change-weather-modification-globally

Púčik et al. (2019) indicate hailstones size of 2 to 3 centimeters (around 1 inch) in diameter damage crops most. Therefore, measuring hailstone size and the frequency of hail events might not be an appropriate approach for evaluating hail suppression program effectiveness. In other words, cloud seeding might reduce the frequency and magnitude of hailstones but could potentially cause more damage. The effectiveness of cloud seeding on crop loss remains ambiguous.[3]

Only a few studies examine the effectiveness of hail suppression programs on crop damage and productivity. Soviet scientists provided hail suppression by launching rockets into clouds, reporting a 50% to 90% reduction in crop hail damage (Federer et al., 1986). Abshaev et al. (2023) indicated that over the past 65 years, Russia improved its rocket seeding technology, thereby reducing hail crop damage by as much as 86%. In the US, Knowles and Skidmore (2021) found that cloud seeding in North Dakota resulted in a 13% increase in wheat yields per harvested acre and a 0.548 decrease in the wheat loss ratio in North Dakota. According to research by Ekland et al. (1999), cloud seeding reduced the crop loss ratio by 27% in Kansas and minimized damaged planted areas by 34% to 48%.

One concern regarding cloud seeding for hail suppression is the potential reduction in rainfall in downwind areas. When a downwind region receives less precipitation or more hailstones after cloud seeding in the target areas, it is referred to as the downwind effect. This effect has been a concern for northwest Kansas counties that terminated cloud seeding programs. However, while the downwind effect has been discussed in the context of cloud seeding for rain enhancement purposes, it has not received much attention in the hail suppression context (Solak et al., 2003; DeFelice et al., 2014; Wang et al., 2019). Only a few studies have explored the potential rainfall changes in hail suppression areas. For example, the Kansas Water Office, responsible for cloud seeding operations in Kansas, reported a decrease of 0.25 inches in average precipitation during the growing season in the targeted areas (Eklund et al., 1999). Conversely, in Alberta, there was a 2.2% increase in rainfall in hail suppression areas (Krauss and Santos, 2004).

When policymakers decide whether to continue a policy, providing an evaluation of

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[3] The relationship between hail magnitude and damage also depends on growth stage of crop, canopy position of crops, weather, and water management (Holman et al., 2022). For example, cotton is more vulnerable to hail in the bud stage than in the boll stage (McGinty et al., 2019; Yue et al., 2019).

its efficacy is crucial. In the literature, the most common measurements are the size of hailstones and the frequency of hail events. In this study, we use a broader set of measurements to evaluate the efficacy of the cloud seeding program, including its impact on hailstone size and frequency, crop damage, and crop yields, while also considering potential downwind effects. The purpose is to evaluate the degree to which choosing different measurements may lead to different conclusions. When different measurements yield conflicting conclusions, it can spark discussions and encourage collaboration to improve the technology or management of the program.

Kansas serves as a fitting focal point for this analysis due to its status as a prominent producer of winter wheat, corn, and sorghum in the US, and the significant hail damage experienced by its crops. We use county level data over the 2002-2020 period for Kansas in this paper. As a prelude to the full set of findings, the analysis shows that cloud seeding is associated with reductions in hail size in target areas. Even though the size of hailstones decreases, there are no statistically significant reductions in hail or drought damage. However, the results indicate that cloud seeding is associated with more flooding damage to crops. This finding is consistent with the literature that severe rain or inundation can occur in target areas after cloud seeding (Almheiri et al.,2021; Spiridonov et al., 2015; Tuftedal et al., 2022; Yoo et al., 2022). Lastly, the findings indicate that cloud seeding enhances corn productivity within the seeding area but diminishes sorghum productivity in downwind areas. Leveraging these outcomes, we conduct a cost-benefit analysis of the Kansas cloud seeding program. While the overall net present value of the program is positive, it is essential to recognize that this is not universally beneficial; certain counties, particularly those downwind, exhibit negative net present values.

The remaining sections of this paper are structured as follows: Section II provides an introduction to cloud seeding in Kansas. The methodology and data are outlined in Sections III and IV, respectively, followed by the presentation of results in Section V. Section VI presents the cost-benefit analysis. Finally, conclusions and policy implications are discussed in Section VII.

II. Background

This section begins with a discussion of the primary rationale behind considering cloud seeding as a promising method of reducing hail. We also provide an overview of research findings related to cloud seeding efficacy. The section concludes with a detailed discussion of the Kansas cloud seeding project.

(1) Cloud seeding for hail suppression

The hail formation process is well-documented in the literature (Allen, 2020). Two primary components are essential for hailstone production: supercooled water and embryos. Supercooled water refers to liquid water persisting below the freezing point of pure water for an extended duration. This phenomenon often occurs in convective cloud systems where updrafts bring cloud condensation nuclei (CCN) into the cloud. Condensation of water vapor on these CCNs results in the formation of supercooled water droplets.

The merging of supercooled water droplets, typically due to contact with embryos, initiates a chain reaction of freezing processes, leading to the formation of hailstones. Small hailstones may revert to embryos, attracting more supercooled water, sustaining the freezing process, and allowing for further growth. Hailstones eventually fall when they reach a size too substantial to be supported within the clouds.

According to microphysical theory, the core concept behind cloud seeding is to stimulate beneficial competitiveness processes. This theory posits that natural embryos in clouds, such as dust or pollen, may not be plentiful enough. Consequently, the introduction of artificial embryos, like silver iodide or dry ice, can compete with natural embryos, preventing the overharvesting of supercooled water droplets by natural embryos. The expected result is that all hailstones should be smaller than those without seeding. Smaller hailstones have the potential to melt before reaching the ground, effectively mitigating potential hail damage.

The promise of controlling hail damage through cloud seeding led to extensive investigations dating back to the 1970s. During this period, several multi-year projects aimed to explore the beneficial competitiveness hypothesis and assess the feasibility of cloud seeding technology.

From 1972 to 1976, the National Hail Research Experiment (NHRE) spanned multiple states in the US, including Northeast Colorado, Kansas, Nebraska, and Wyoming. However, the results revealed no statistically significant effects in reducing the frequency and size of hail (Allen et al., 2020; Foote et al., 1979; Knight and Squires, 1982; Squires and Knight, 1982). Subsequent to NHRE, from 1977 to 1982 Switzerland, Italy, and France initiated the Grossversuch IV project to test Soviet hail suppression technology. Similar to the NHRE, the results demonstrated no statistically significant difference in hail frequency and magnitude between seeded and non-seeded areas (Federer et al., 1986). A reexamination of the Grossversuch IV project data by Auf der Maur and Germann (2021) even suggested that cloud seeding might increase the kinetic energy of hailfall, potentially intensifying damages.

Despite inconclusive results from experimental projects, countries worldwide persisted in their investment in cloud seeding for hail suppression. Real-world seeding data played a pivotal role in evaluating the efficacy of these programs. In Slovenia, Serbia, and Argentina, no statistically significant changes were observed in either the frequency or magnitude of hailstorms (Bergant, 2011; Gavrilov et al., 2013; Rivera et al., 2020). Greece and Spain witnessed a reduction in hailstone magnitude without a significant impact on frequency (Spiridonov et al., 2015; Dessens et al., 2016). In contrast, A study in France indicated that cloud seeding resulted in a substantial decrease in both the frequency and magnitude of hailstones (Changnon, 1971). These diverse outcomes highlight the complexity and variability in the effectiveness of cloud seeding initiatives across different geographical regions.

(2) Weather modification in Kansas: A four-decade cloud seeding initiative

Cloud seeding has been a cornerstone of weather modification efforts in the US for six decades. Among the states actively adopting cloud seeding, Kansas, along with North Dakota and Texas, stand out, implementing this technique primarily during the warm season[4]. The focus in these states has been on hail suppression and rain enhancement, with occasional applications for fog dispersion.

[4] Several states in the US have implemented cloud seeding during different seasons and for various purposes. States such as California, Nevada, Idaho, Utah, Wyoming, and Colorado employ cloud seeding in the cold season for snowpack augmentation and rain enhancement, with primary objectives aimed at increasing water storage in reservoirs and replenishing groundwater. While cloud seeding has been proven to increase rainfall and runoff by an average of 10% to 20% (Rosenfeld and Woodley, 1989; Bruintjes, 1999; Flossmann et al., 2019), its efficacy for hail suppression remains a subject of controversy.

To emphasize the risk and exposure to hail, Figure 1 illustrates the distribution of severe hail—defined as hailstones over 1 inch (25.4 mm) in diameter—across the US[5]. The map depicts the significant threat posed by hazardous hail events, particularly in the Great Plains region, including Kansas. In 2022 alone, Kansas experienced 289 major hail events, ranking it fourth among states in hailstone frequency after Texas, Nebraska, and Minnesota. This highlights the pressing demand for effective measures to abate the costly impact of severe hailstorms[6].

Among the states, Kansas leads in winter wheat and sorghum production in the US and ranks among the top ten states for corn production. Agriculture contributes $81 billion to Kansas's economy, with approximately 88% of the state's land dedicated to farmland for crops and livestock. According to the Kansas Crop Planting Guide[7], winter wheat should be planted from mid-September to late October, varying depending on geographic zones, with harvest taking place the following summer. Corn and sorghum are typically seeded between late April and mid-May. However, vulnerability to hailstorms, prevalent from April to September, poses a threat to the pre-mature stages of wheat and silk corn, leading to potential crop yield losses. The rapid onset of damage within minutes makes cloud seeding programs desirable in Kansas to mitigate forecasted crop-damaging hail.

The Kansas Water Authority is the key entity managing the cloud seeding program in Kansas[8]. In the 1990s, the western part of Kansas was the primary target for cloud seeding. However, a five-year program faced suspension due to protests led by the grassroots group, Citizens for Natural Weather[9]. Their opposition was not rooted in doubts about hail suppression efficacy but in concerns that seeding clouds might alter local and adjacent precipitation patterns. In 1999, four northern Kansas counties voted to withdraw from the cloud seeding program. The present study focuses on the southwestern part of Kansas, where 14 counties agreed to participate in the cloud seeding program in 2002 as shown in Figure 2 (blue area).

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[5] The National Centers for Environmental Information (NCEI) identifies severe hail based on the diameter of hailstones. Appreciable damage occurs only when the diameter is over 1 inch (25.4 mm). The threshold for damaging hail size was adjusted in 2010 from 19.1 mm to 25.4 mm, as suggested by stakeholders (NCEI, 2009). It's worth mentioning that larger hailstones tend to be less spherical (Allen, 2020).

[6] See: https://www.iii.org/table-archive/22795.

[7] See: https://bookstore.ksre.ksu.edu/pubs/l818.pdf.

[8] Kansas Water Authority is within and as part of the Kansas Water Office.

[9] See: https://www.latimes.com/archives/la-xpm-2000-jun-11-mn-39711-story.html

The Kansas Water Office executed an Operational Plan for the Weather Modification Project, where the project manager made daily seeding decisions based on the Operation Plan and meteorological data during the program's active period[10], typically from April to September. On a daily basis, the project manager assesses all available data to determine the seedability of incoming clouds. If a seeding decision is made, the project manager contacts the pilot and crew to confirm the seeding strategy. Following mission completion, pilots report cloud responses and data to the operation center for analysis. The Operation Plan acknowledges the potential spillover effect in adjacent areas, impacting not only the downwind but also the upwind areas, with buffer zones set at 25 and 10 miles, respectively.

Cloud seeding programs in Kansas have dual objectives, focusing on both hail suppression and rain augmentation. According to the Operation Plan, hail suppression generally takes precedence over rain augmentation. However, adjustments are made based on soil moisture levels and crop growth stages, with priority given to areas vulnerable to hail risks. Additionally, when a convective cloud system is unstable, the seeding mission shifts from rain augmentation to hail suppression. Operation records align with the Operation Plan, revealing that from 2002 to 2020, cloud seeding days were 65% for hail suppression and 35% for rain augmentation, as illustrated in Figure 3. Nevertheless, the number of counties participating in the cloud seeding project has declined over time, with no Kansas counties in the program since 2017 (see Figure 4). As of 2022, Kansas is no longer affiliated with the North American Weather Modification Council.

[10] Meteorological data comprise hourly observations, aviation terminal forecasts, severe weather warnings, synoptic surface and upper air analyses, storm data within the operational area, and satellite imagery.

III. Methodology

The Kansas cloud seeding program is a jointly funded initiative involving the state and county governments, with the state contributing \$240,000 annually for radar systems and counties determining their participation and funding based on population. Using a framework adapted from Hettich and Winer (1984, 1988) and Brien and Eger III (2021), the decision-making process is modeled as a competitive dynamic where governments aim to minimize their contributions while ensuring public good provision, driven by officials seeking to maximize voter support rather than acting altruistically. Readers can find full model in Appendix A.

Based on the model, three major hypotheses are tested in this study:

Hypothesis 1: Based on the concept of beneficial competition (Detwiler, 2002), participation in a cloud seeding program reduces the frequency and intensity of hailstorms in the target area.

Hypothesis 2: Participation in a cloud seeding program reduces hail damage to crops in target areas.

Hypothesis 3: A spillover effect exists in cloud seeding programs for hail suppression and rain enhancement in downwind areas.

The main idea of cloud seeding program as a damage control agent is based on the concept of beneficial competition (Detwiler, 2002). It assumes that hailstorm frequency and magnitude are functions of cloud seeding, where artificial embryos are introduced into the clouds to compete with natural embryos in supercooled water. The result is an increased production of smaller hailstones that hopefully melt before hitting the ground. Additionally, we test for the presence of and determine whether spillovers are positive or negative. Consequently, cloud seeding potentially reduces crop damage.

To achieve this goal, panel data and the specification presented in equation (1) are employed. In equation (1), m_i controls the characteristics of county *i* that do not vary over a short period, such as altitude, referred to as county-fixed effects. Additionally, λ_t represents time fixed effects, which is included in the model to account for unobserved, time-specific factors—such as El Niño—that could influence the dependent variable across all counties. . Controlling for county and time effects helps to insure the comparability of all observations.

$$Y_{it} = \alpha \cdot seeding_{it} + \beta \cdot UWseeding_{jt} + \gamma \cdot X_{it} + m_i + \lambda_t + \mu_{it} \quad (1)$$

Y_{it} represents a set of outcome variables in county *i* in year *t*. We examined several outcome variables that include hail frequency, hail magnitude, crop damage, and crop production. The variable $seeding_{it}$ denotes the cloud seeding program participation in county *i* in year *t*, where 1 indicates participating in cloud seeding program, and 0 otherwise. The parameter α captures the marginal effect of the cloud seeding program participation on outcome variables. Additionally, $UWseeding_{it}$ denotes the seeding decision in upwind county *j* of county *i* in year *t*, with 1 indicating seeding and 0 otherwise. The parameter β captures the spillover effect on outcome variables from the upwind seeding county on downwind county. The vector X_{it} includes covariates such as moisture and temperature, will be discussed further in the Data section below. Finally, μ_{it} denotes the error term.

IV. Data

For testing the hypotheses presented above, data from various sources are compiled:

(1) Cloud seeding data

The cloud seeding data used in this study are derived from the National Oceanic and Atmospheric Administration (NOAA). In compliance with Federal Law[11], all weather modification activities are mandated to submit weather modification project reports to NOAA. For the Kansas cloud seeding program, based on cloud conditions the program operator will call the pilots to standby for data collection or seeding missions. Once the pilots seed the clouds, it will be recorded in the NOAA report. Even if a hailstorm travels into a non-participating county, the program operator cannot require the pilot to execute a seeding mission beyond the boundary of the participating county. Therefore, cloud seeding activities only occur within the boundaries of participating counties. The dataset spans from 2002 to the present and includes information on the counties participating in cloud seeding program.

(2) Hailstorm and weather data

Hailstorm data is obtained from the Next Generation Weather Radar (NECRAD). This dataset provides comprehensive information about the location and magnitude of each hailstorm. The frequency of hail is determined by the total number of hailstorms that

[11] Public Law 92-205, or "Weather Modification Reporting Act of 1972".

occurred during the growing season. The dataset spans from 1955 to 2022 and is aggregated at the county level during the growing season.

Other weather-related data are extracted from the NOAA Climate Data Online (CDO) dataset, which comprises weather observations from various stations. Data for each county are aggregated from various stations within the county. The dataset includes information such as maximum and minimum temperatures. From these data, we computed Growing Degree Days (GDD) and Stress Degree Days (SDD) during the growing seasons, from April to September, using the following formula:

$$GDD = \max\,(0,\ \frac{T_{max} + T_{min}}{2} - T_{base})$$

For GDD, the equation considers the daily mean temperature, calculated as the average of the daily maximum temperatures, T_{max}, and minimum temperatures, T_{min}. T_{base} represents the base temperature for crop growth, which varies by crop type. Specifically, it is set at 40 degrees Fahrenheit for winter wheat (McMaster and Smika, 1988) and 50 degrees Fahrenheit for corn (Cross and Zuber, 1972). If the mean temperature falls below base temperature, GDD is set to zero. The GDD accumulates throughout the growing season. Based on the empirical strategy, we calculated three distinct GDD values for winter wheat, sorghum, and corn. When estimating the impact on crop productivity, we used crop-specific GDD for each crop. For analyzing the impact on crop damage, we chose a base temperature of 40 degrees Fahrenheit, given that winter wheat is the predominant crop in Kansas. This explanation is also included in the section describing the GDD calculation.

For SDD, the formula involves subtracting the upper temperature threshold $T_{threshold}$ from the daily maximum temperature T_{max}. If T_{max} is below $T_{threshold}$, SDD is set to zero. The upper temperature threshold is consistent at 86 degrees Fahrenheit for all crops (Cross and Zuber, 1972). When temperatures exceed 86 degrees Fahrenheit, crops may either cease growth or incur damage.

$$SDD = max\,(0, T_{max} - T_{threshold})$$

On a different note, crop growth relies on adequate moisture. The Palmer Z index, a measure of moisture deviation from normal climate on a monthly basis, is employed. This index, obtained from NOAA[12], distinguishes between wet and dry conditions. Following Knowles and Skidmore (2021), the variables for dryness Dry_{it} and wetness Wet_{it} are calculated as:

$$Dry_{it} = -\min(0, PZ_{it})$$

$$Wet_{it} = max(0, PZ_{it})$$

A higher count of Dry_{it}/Wet_{it}, indicating a greater deviation from the normal climate, indicates drier/wetter conditions in the county during the growing season. According to NOAA, if Dry_{it} falls between 0 and 1.24, it indicates a normal climate, while a value above 2.75 indicates extreme drought. Similarly, if Wet_{it} falls between 0 and 0.99, it indicates a normal climate, and a value above 3.50 indicates extreme wetness. From Table 1, on average, the moisture in Kansas during growing seasons is near normal.

(3) Crop data

Crop indemnity data is obtained from the USDA Risk Management Agency Cause of Loss Historical Data Files. These data provide information on indemnity payments and loss ratios for different perils, including hail, drought, and excess moisture (i.e. flood)[13]. The crop loss ratio is defined as the total indemnity divided by the total premium. The total premium comprises the premium paid by farmers plus public subsidy. The target crop loss ratio for US crop insurance is 0.88, indicating that the insurance company retains 12% of the premium to cover unexpected shocks. If the loss ratio exceeds 1, the insurance company is in an unsustainable situation. Additionally, crop yield data for winter wheat, corn, and sorghum, the top three major crops in Kansas, are included in the analysis. The crop yield data are measured in bushels per acre and are sourced from the USDA[14].

(4) Wind direction data

The wind direction data is obtained from the National Aeronautics and Space Administration Land Data Assimilation System 2 (NLDAS-2) dataset, with a resolution of 0.25 degrees[15]. Using QGIS version 3.32.3, wind speed and directions were calculated

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[12] See https://www1.ncdc.noaa.gov/pub/data/cirs/climdiv/
[13] In Kansas, 35.8% of indemnity is due to drought, 17.5% due to flood, and 8.2% due to hail.
[14] See USDA National Agricultural Statistics Service: https://quickstats.nass.usda.gov/
[15] 1 degree is equal to 69 miles.

based on zonal velocity (U wind) and meridional velocity (V wind)[16]. In Kansas, the prevailing wind during the growing seasons (April to September) generally comes from the west, as depicted in Figure 5. This wind direction data is crucial for identifying downwind areas.

Table 1 presents a summary of descriptive statistics. The data gathered from various sources form an unbalanced panel, so the observation numbers differ for each variable. The maximum recorded hail frequency is 94, indicating that 94 hailstorms were observed in one county during the growing season (April to September), with an average of 10.32 hailstorm occurrences during the growing season. Furthermore, the magnitude of hailstorms is evaluated based on the diameter of hailstones. On average, the diameter of hailstones is 1.13 inches, which exceeds the threshold that causes damage to crop plants. The largest hailstone recorded during the period of analysis in Kansas is 3 inches. Additionally, note that the loss ratios for different perils are above 0.88, the design ratio of the USDA. This suggests that the indemnity caused by extreme weather events might be underestimated, and the premium may not be sufficient to cover the indemnity. Table 2 summarizes the definitions and data sources of the variables used in this study.

[16] The wind data from NASA is 10 meters above the surface. Although NOAA provided wind data under 17 levels, the resolution of data is 2.5-degree latitude x 2.5-degree longitude global grid.

V. Results and discussion

In this section, we first present the core results obtained using all counties in Kansas. To explore the robustness of the findings, we conduct propensity score matching to establish a subsample by incorporating nearby counties from adjacent states, Colorado and Oklahoma, into the evaluation. Results using the combined sample of adjacent counties and all counties in Kansas are also provided. For more details about the propensity scores and results, please refer to Appendix C. Based on the estimate results, cost-benefit analysis is provided in the last part of this section.

(1) Estimating the cloud seeding program impacts in Kansas

Table 3 presents the regression results and estimated effects of the cloud seeding program on hail frequency and magnitude for all Kansas counties. The average size of hailstones in Kansas is 1.13 inches, exceeding the size threshold that might potentially cause damage to crops. The results indicate that cloud seeding programs show no statistically significant effect on hailstorm frequency in target counties or downwind counties. However, estimates indicate that hail size diminishes by 0.098 inches in target areas, which is about 8%, but there is again no statistically significant effect on hail size in downwind areas. In short, these results are consistent with the literature; the evidence suggests that the cloud seeding program may not have a statistically significant impact on hailstorm frequency and magnitude, or the impact is negligible (Bergant, 2011; Gavrilov et al., 2013; and Rivera et al., 2020).

Additionally, insufficient moisture in the air as measured by the Dry index correlates with decreased hail frequency and magnitude. Moreover, there is an increase in rainfall of about 0.259 inches in targeted regions, representing approximately 7.3%, with a corresponding decrease of 0.077 inches in downwind areas, although this decrease is statistically insignificant. These results suggest that cloud seeding has not resulted in the "rain steal" phenomenon in this region.

Also, of interest is whether there is evidence that cloud seeding reduces crop damage. In Table 3, the regressions results examining the impact of the cloud seeding program on the crop loss ratio in Kansas are presented. The table reveals that the cloud seeding program had no statistically significant impact on the crop hail loss ratio or the crop drought loss ratio. This finding may be due to the fact that even though the hail size is estimated to be reduced by 0.098 inches, on average the hail size is still above the 1 inch threshold.

However, the analysis also reveals that the cloud seeding program is associated with an increase in crop flooding damage. Flooding damage, indicative of excessive precipitation, can impede farmers' ability to sow crops or lead to crop damage. As detailed in Table 3, the cloud seeding program results in a notable rise in the flooding crop loss ratio by 0.541, around a 32% increase with a 99% level of significance[17]. The existing literature may provide evidence to support the crop flooding damage resulting from cloud seeding. Following cloud seeding missions for hail suppression, target areas tend to experience heightened precipitation of 10% to 12% (Spiridonov et al., 2015; Tuftedal et al., 2022).

Furthermore, in cases where the cloud seeding mission is aimed at rain augmentation, the target areas often encounter even more substantial increases in precipitation. Drawing from experiences in other warm-season cloud seeding countries, Almheiri et al. (2021) conducted intensity-duration-frequency curves, revealing heightened rainfall intensities post-cloud-seeding missions and elucidating the potential reasons behind the significant urban inundation experienced by the United Arab Emirates in 2007 after seeding. Similarly, Yoo et al. (2022) observed a significant increase in runoff by approximately 60% in Korea following cloud seeding. In Texas, individual cells witnessed a 50 to 100% surge after seeding (Texas Natural Resource Conservation Commission, 1997).

Additionally, researchers assert that the speed at which rainfall occurs is understudied. In the natural environment, storms usually endure for only two to six hours, and rainfall or hail may fall steadily. However, experimental evidence suggests that cloud seeding can trigger the generation of more hailstones or rainfall within a 30-minute timeframe. This implies that precipitation is concentrated in a shorter duration, potentially explaining the elevated flooding crop loss ratio observed after cloud seeding programs.

We also explored whether cloud seeding contributes to increased crop production or crop yield by mitigating hail damage or enhancing rainfall. Table 3 presents the impacts of cloud seeding on major crops, namely winter wheat, corn, and sorghum. Cloud seeding has no statistically significant effect on wheat or sorghum production in the target counties.

[17] It is worth noting that the US crop insurance typically reserves a 12% premium for severe and unexpected disaster losses, a sum considerably lower than the observed increase. This suggests that the elevated flooding crop loss ratio could present challenges to the financial sustainability of crop insurance companies. In the long term, there may be implications for increased insurance premiums and subsidies.

However, there is a statistically significant increase of 17.8 bushels per harvested acre in corn yield, accounting for approximately a 15.0% increase. Conversely, in downwind counties, the spillover effect of the cloud seeding program results in a significant decline of sorghum productivity by approximately 10 bushels per harvested acre, reflecting a decrease of around 14.8%.

A potential explanation for these findings is that winter wheat can thrive in dryland conditions, but production and yield may decline when moisture levels are excessively high. These findings align with the patterns observed in Table 3. Also, less moisture as measured by the variable Dry significantly decreases production and yield on crops, but it affects wheat less than corn and sorghum. As anticipated, GDD contributes to increased crop production and yield, while SDD is linked to decreased production and yield. However, different crops exhibit varied responses to the Wet variable[18].

(2) Estimating the cloud seeding program impacts in West Kansas

In the Table 4 weather variable columns, the cloud seeding program similarly shows no statistically significant impact on hailstorm frequency. In the West Kansas sample, the cloud seeding program increases hail magnitude in downwind areas by 0.11 inches, approximately 9%.

In the Table 4 crop loss ratio column, despite the increase in hail magnitude due to the upwind cloud seeding program, the hail loss ratio does not exhibit a corresponding increase in the downwind areas. According to the results, the cloud seeding program is not statistically significant in the hail loss ratio regression. As observed in Table 3 crop loss ratio column, the cloud seeding program also raises the crop flooding loss ratio by 0.504 (30.83%). Less moisture, as indicated by Dry, increases the loss ratio of drought and flooding on crops. As mentioned earlier, intense precipitation is sometimes observed after seeding events, and the intense precipitation can cause flooding, especially if the soil is dry. Therefore, if the Dry indicator deviates more from normal weather conditions, damage to croplands is more likely when intense precipitation occurs[19].

[18] Corn vs. Grain Sorghum in Water Limited Scenarios: https://www.cropquest.com/corn-vs-grain-sorghum/#

[19] See World Food Program "Why do floods follow droughts? Look to the Somali Region of Ethiopia". https://www.wfpusa.org/articles/floods-follow-droughts-ethiopia/

The estimated effects of cloud seeding on crop productivity in Table 4 are similar to Table 3. The cloud seeding program improves corn productivity in the seeded area by 8.5 per bushel per harvested acre, around 7%. However, the magnitude in West Kansas sample is smaller than the full Kansas sample. However, the cloud seeding program decreases sorghum productivity in downwind areas by 10.146, around 16.23%, which is similar to the result of full Kansas sample.

To summarize, the evidence presented in this paper provides some evidence that there is a statistically significant impact on hailstorm magnitude but not frequency. Moreover, I found no evidence that cloud seeding reduced hail and drought indemnities on crops. However, the analysis suggests that cloud seeding may have unintentionally resulted in increased losses from excess moisture (i.e. flooding) in seeding areas. Finally, the results suggest that there are spillover effects of the cloud seeding program on downwind areas, and the results are robust among different samples. Cloud seeding is associated with an increase in corn productivity in seeded areas and a decrease in sorghum productivity in downwind areas. These findings may be because corn favors more moisture, while sorghum is sensitive to excess moisture and flooding. While I found that the cloud seeding program has an impact on crop productivity, the mechanism might not be due to the beneficial competitiveness hypothesis but unintended changes in precipitation patterns, such as increasing intense rainfall.

(3) Cost-Benefit analysis of cloud seeding program

The cloud seeding program in Western Kansas Groundwater Management District No. 1 aims to preserve water resources and reduce hail damage. Evidence shows that the program increases precipitation by 0.26 inches during the growing season, which benefits water resource management. However, it also raises crop loss ratios due to unintended flooding. While the value of aquifer recharge is beyond the scope of this study, the flood damage to crops is reflected in yield data. Including both would lead to double-counting. This analysis uses changes in crop productivity, such as corn yield, as a proxy to assess the economic value of water resource enhancement and flood damage.

3.1 County government perspective

County officials in Kansas, where agriculture accounts for over 40% of GDP in most participating counties (see Figure 6), prioritize decisions that benefit farmers to gain political support. In this analysis, the benefits of cloud seeding include productivity gains, while costs encompass spillover effects and program expenses.

The net social benefit (NSB) for each participating county from 2002 to 2016 is calculated as the difference between social benefits and costs, expressed in real terms (2002 dollars). Since county governments typically make short-term budget decisions without discounting long-term benefits, costs and benefits are converted to real terms using the Consumer Price Index with 2002 as the base year. Additionally, the net present value (NPV) is calculated using Equation (3):

$$NPV = \sum_{t=0}^{T} \frac{NSB_t}{(1+r)^t} \tag{3}$$

Here, NSB_t represents net social benefits in year t, and r is the discount rate sourced from the Office of Management and Budget for 2002. Sensitivity analysis is conducted using real discount rates of 3.1% and 3.9% for 10-year and 30-year projects, respectively.

The program costs include state and county government budgets. The state budget is derived from the Kansas Water Office, while county budget data comes from the Kansas Department of Administration. Where specific county data is unavailable, the average expenditure across participating counties, approximately $19,225 annually, is used. The total annual cost of the cloud seeding program is approximately $367,880, including fixed and variable costs.

The benefits are calculated based on changes in crop productivity. The productivity gain for corn is 8.5 bushels per acre, while sorghum experiences a loss of 10 bushels per acre in downwind counties due to spillover effects[20]. These yield changes are multiplied by harvested acres and average crop prices in Kansas, with data sourced from the USDA National Agricultural Statistics Service[21].

Table 5 presents the results of the cost-benefit analysis. Net benefits vary by crop type, years of program participation, and spillover effects. Most participating counties show positive net benefits. For instance, Stevens County, which participated for two years, generated a net benefit of $4 million. In contrast, Lane and Scott Counties, with prolonged participation, experienced negative net benefits due to significant spillover effects on sorghum.

3.2 State Government Perspective

The state government's role includes investing in and maintaining program infrastructure, such as radar systems and aircraft. Unlike county governments, the state must account for downwind effects in non-participating counties that experience negative spillover impacts.

Table 6 presents NPV estimates at various discount rates to demonstrate result robustness. Downwind counties incurred cumulative losses of approximately $30 million over the analysis period. In contrast, participating counties gained $40 million, resulting in a net positive benefit[22].

Historical evaluations align with these findings. For example, Eklund et al. (1999) estimated a return ratio of 37 for reduced crop damage in Kansas target counties. Similarly, Knowles and Skidmore (2021) found a return ratio of 37 for a cloud seeding program in North Dakota. In this study, the discounted NPV for 14 target counties in Kansas is $41.3 million, with costs totaling $4.1 million, yielding a return ratio of approximately 10. However, incorporating spillover effects reduces the return ratio to 3. Despite a favorable cost-benefit ratio, the state government terminated the program. This decision may reflect

[20] We also estimate the cost-benefit results using the parameters from Table 3: the productivity gain for corn is 18 bushels per acre, and the productivity loss for sorghum is 10 bushels per acre. Please see Appendix D.

[21] The USDA NASS dataset provides monthly crop prices only, and the price used for the cost-benefit analysis is the average annual crop price.

[22] See footnote 20.

political considerations, as spillover effects resulted in disapproval from negatively impacted counties.

V. Conclusion

Hail damage to agriculture often receives inadequate attention, particularly in regions like Kansas, where frequent hailstorms result in significant crop losses. To mitigate hail damage, Kansas state and county governments implemented a cloud seeding program aimed at suppressing hail and enhancing regional precipitation. This study examines the program's effectiveness by analyzing its impact on hailstorm frequency and intensity, crop damage, and production, while accounting for potential spillover effects.

Using hail frequency and intensity to evaluate the cloud seeding program's efficacy, the findings suggest that the program lacks a statistically significant impact on reducing hail frequency or intensity, or that the observed impact is negligible. These results align with empirical studies from Slovenia, Serbia, and Argentina (Bergant, 2011; Gavrilov et al., 2013; Rivera et al., 2020). While the program decreased the average hailstone size by about 8%, from 1.13 inches to 1.03 inches, the size remains above NOAA's 1-inch threshold for potential crop damage. This may explain why the program does not significantly reduce crop loss ratios associated with hail in this study. Additionally, the program does not appear to reduce crop loss ratios due to drought. However, the program is associated with an increase in precipitation within targeted areas.

An unintended consequence of the program is an increase of approximately 32% to 35% in crop flood loss ratios in cloud-seeded counties, as observed in both Kansas and West Kansas samples. This aligns with earlier findings that precipitation intensity often rises sharply following cloud seeding missions (Almheiri et al., 2021; Spiridonov et al., 2015; Texas Natural Resource Conservation Commission, 1997; Tuftedal et al., 2022; Yoo et al., 2022). Flooding may also result from seeding conducted after drought conditions, where overly dry soil fails to effectively absorb water.

Examining potential downwind effects, the evidence provides no support for a "rain theft" phenomenon; downwind counties do not experience reduced rainfall when upwind counties conduct cloud seeding. Moreover, seeded counties benefit from increased rainfall, which may recharge underground water sources. However, downwind counties experience approximately a 15% reduction in sorghum productivity, while seeded counties see increased corn production of 15.01% and 8.30%.

The findings regarding crop productivity are robust, and the aggregate net benefit and net present value of the cloud seeding program are positive based on the estimations. However, the program's overall outcomes are not entirely advantageous due to potential unintended consequences. Limitations of the study arise from data constraints, particularly the absence of specific information on seeding dates and locations. Using county-level data could overestimate the program's impact because hail damage tends to occur in narrow, localized zones rather than uniformly across entire crop fields.

Given the vast cropland in the U.S., relying solely on crop insurance imposes significant financial burdens on both farmers and taxpayers[23]. Alternative solutions, such as anti-hail nets (Gandorfer et al., 2016; Porsch et al., 2018; Rogna et al., 2021; Rogna et al., 2022), are impractical for large-scale farms due to their cost and limited effectiveness24, as large hailstones can still penetrate these nets (Childs et al., 2020).

Cloud seeding remains a promising approach for reducing hail damage across extensive agricultural areas. Technological advancements, such as uncrewed aircraft systems, hold potential for improving the efficiency and effectiveness of seeding operations (DeFelice et al., 2023). Future discussions should focus on optimizing project design and addressing spillover effects. Introducing compensation mechanisms for affected areas could mitigate negative externalities and enhance the program's sustainability.

More research is essential to better understand the efficacy of cloud seeding and its broader impacts. Continued exploration of this technology is vital for developing innovative, cost-effective solutions to mitigate hail damage and support the agricultural sector.

[23] On average, producers only pay 40% of the premium, see: https://www.ers.usda.gov/topics/farm-economy/farm-commodity-policy/title-xi-crop-insurance-program-provisions/

[24] Average farmland sizes are 60 ha and 11 ha in Germany and Italy, respectively. In the USA, the average farmland size is 445 ha, and it might be the reason why farmers could not establish anti-hail net. Therefore, cloud seeding might be a more cost-efficient way to avoid hail damage.

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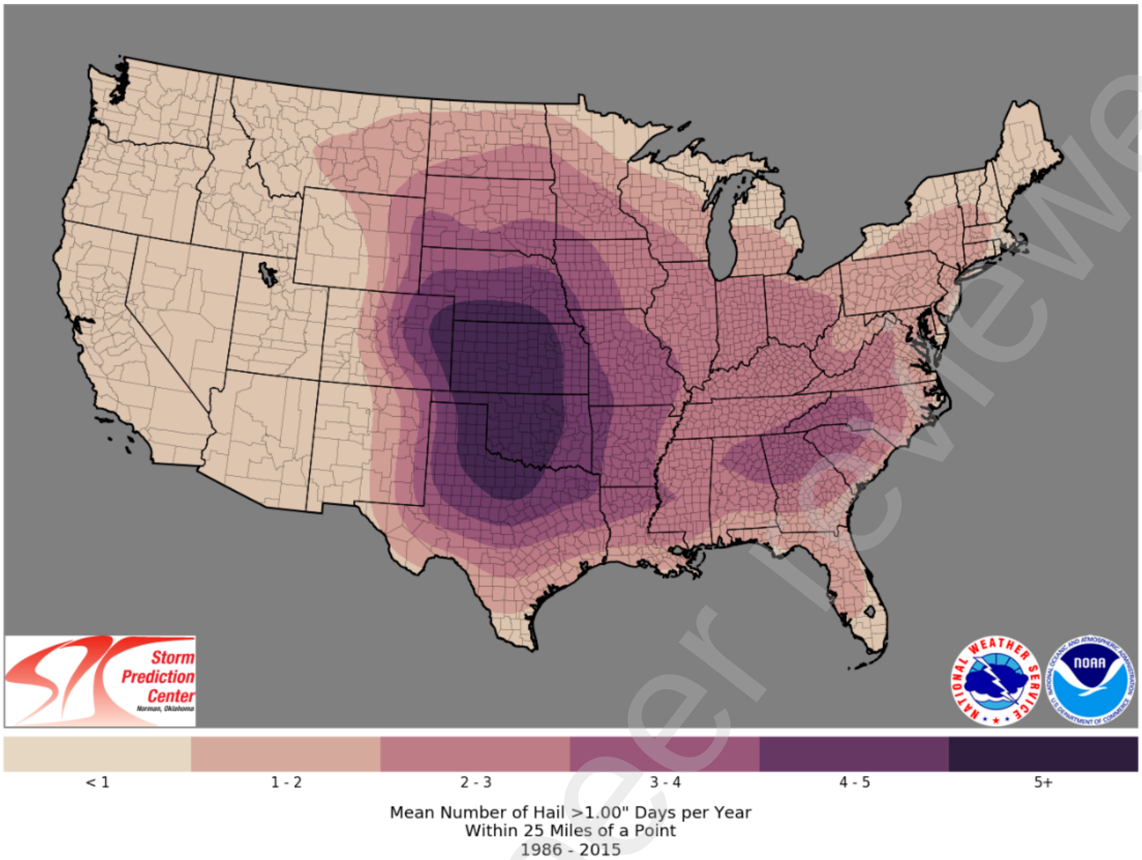
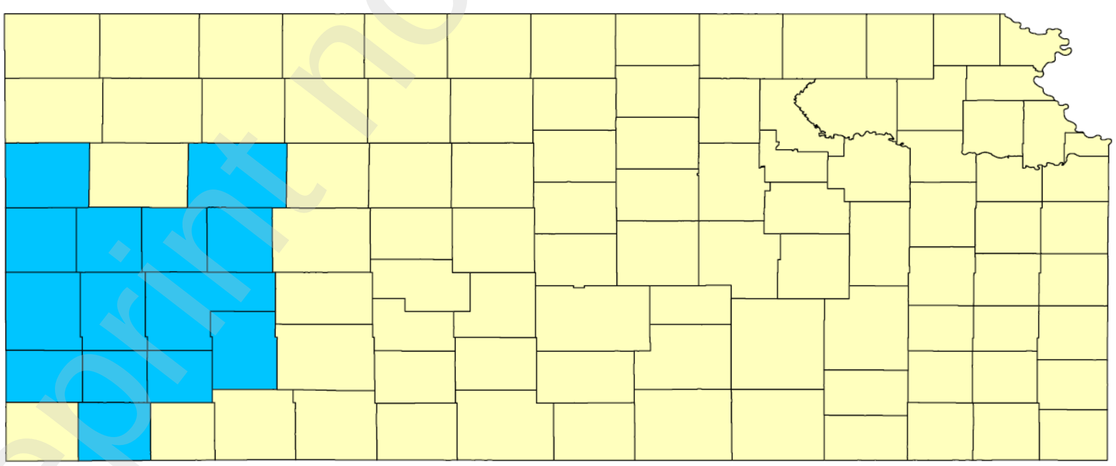


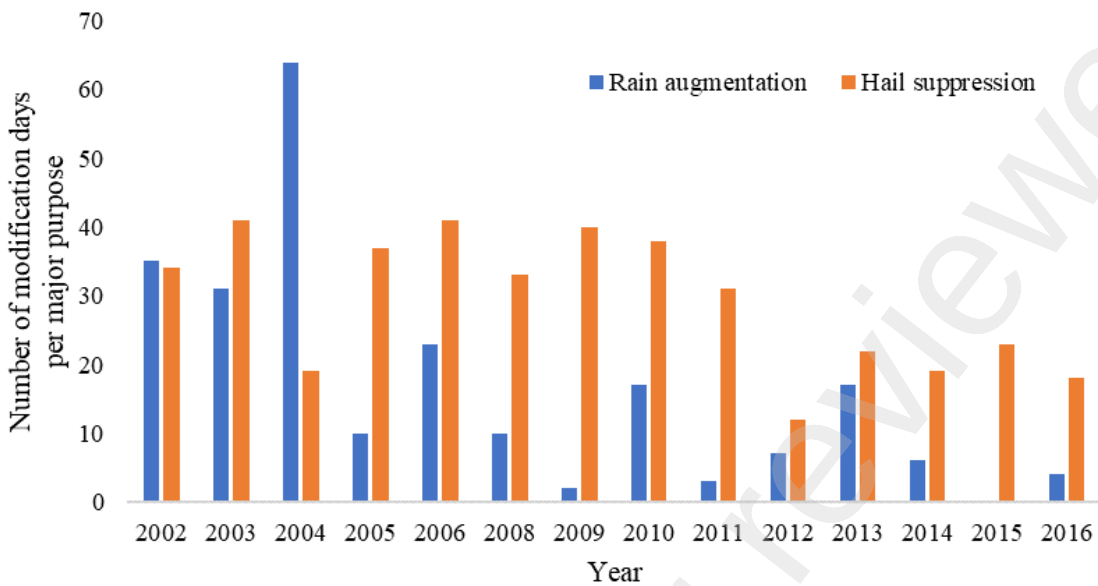
Source: NOAA
According to NOAA, when the hail size exceeds 1 inch, the hailstone might cause potential damage. The entire state of Kansas is covered by hailstorms that cause damage, according to historical data.

Figure 1. Hail distribution in Great Plains



Counties that participated in the cloud seeding program are concentrated in the western part of Kansas, which is particularly threatened by hailstorms, especially in the summer.

Figure 2. Map of counties participating in the cloud seeding project (2002, Kansas)



Data source: NOAA.

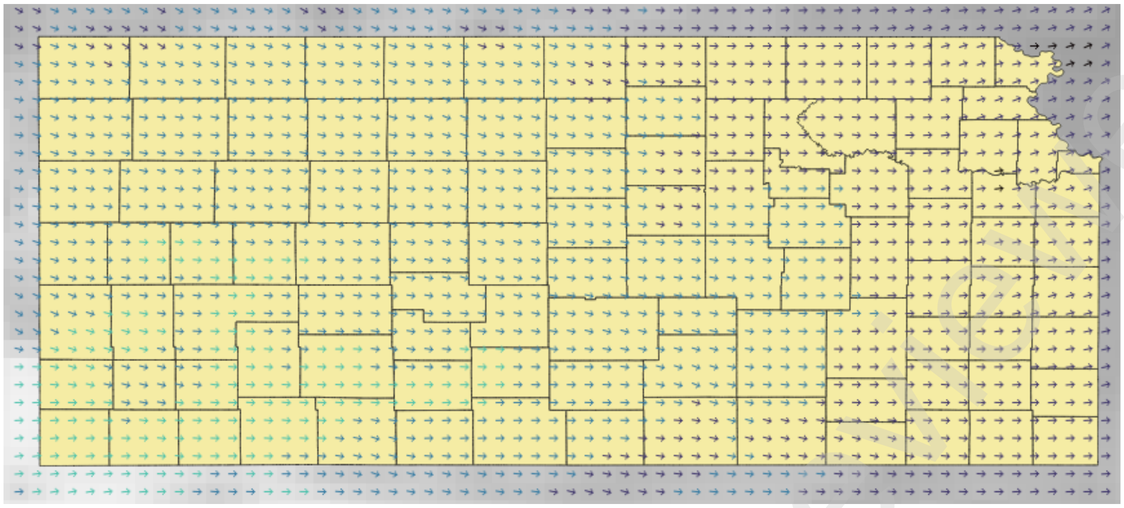
According to NOAA's report, this figure indicates the days with different seeding missions each year. Approximately 65% of the days were dedicated to hail suppression missions.

Figure 3. Number of modification days for hail suppression and rain enhancement in Kansas

Data source: NOAA.

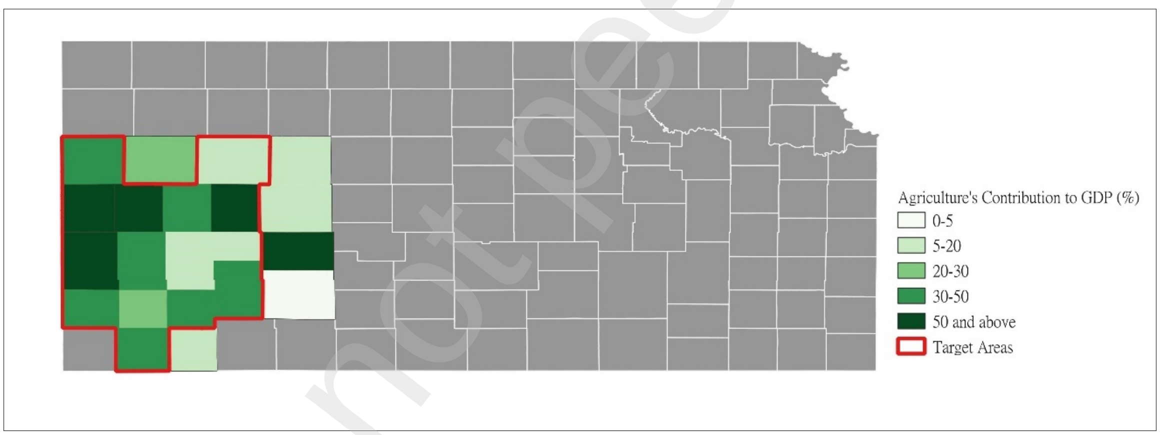
In total, there are 105 counties in Kansas, and 14 counties participated in the cloud seeding program, with participation decreasing over time. The 2007 data is missing from our dataset.

Figure 4. Numbers of counties participating in Kansas cloud seeding program



The prevailing wind direction in Kansas during the growing season is from west to east. Based on this map, we can identify the downwind counties.

Figure 5. Wind direction in Kansas (2003 July)[25]



Most of the counties that participate in the cloud seeding program have a high contribution of agriculture to the county GDP.

Figure 6. Agriculture's Contribution to County GDP (Percentage)

[25] The Kansas shapefile is from USGS National Boundary Dataset: https://www.sciencebase.gov/catalog/item/59fa9f5de4b0531197affb31

Table 1 Descriptive Statistics for Kansas Sample (County-Level Data, 2002–2020)

Variable*	Obs**	Mean	Std. dev.	Min	Max
Weather					
hail frequency (times/year)	1,890	10.32	8.78	0	94
hail magnitude (inch)	1,890	1.13	0.33	0	3
rainfall (inch)	1,881	3.55	1.30	0.69	9.10
Loss Ratio					
Hail	1,540	2.90	1.69	0.02	17.71
flood (excess moisture)	1,817	1.70	0.99	0.22	8.82
Drought	1,841	2.37	1.10	0	9.78
Yield (bushel per acre					
Sorghum	1,418	67.32	22.92	13	134
winter wheat	1,855	40.82	10.12	12.1	80
Corn	1,654	118.72	38.24	18	225
Production (1,000 bushel)* **					
Sorghum	1,418	2,090	1,908	9.4	12,400
winter wheat	1,855	3,308	2,764	9.0	18,500
Corn	1,654	4,961	5,042	14.8	32,400
Environmental					
GDD40	1,842	3923	835	0	5150
GDD45	1,842	3344	725	0	4535
GDD50	1,842	2770	617	0	3922
SDD86	1,842	487	242	0	1532
Dry	1,890	0.43	0.70	0	3.52
Wet	1,890	0.60	0.79	0	4.46

* Data pertain to the entire year and are not restricted to the cloud seeding season.
**The sample is unbalanced, with varying numbers of years included for each county.
*** This represents the total annual production for each county in Kansas, measured in thousands of bushels.

Table 2. Variable definitions

Variable name	Definition	Data Source
Hail frequency	Total number of hailstorms occurs in growing season in county *i*	Next Generation Weather Radar
Hail magnitude	Average diameter of hailstones in growing season in county *i* (inches)	Next Generation Weather Radar
Rainfall	Average rainfall in growing season in county *i* (inches)	NOAA Climate Data Online
Seeding	Participation in a cloud seeding program by county *i* (0 and 1)	NOAA
UWseeding	Participation in a cloud seeding program by upwind county of county *i* (0 and 1)	NOAA and NLDAS-2
Dry	Drought severity deviates from normal weather conditions and is calculated using the Palmer-Z index.	NOAA
Wet	Wetness severity deviates from normal weather conditions and is calculated using the Palmer-Z index.	NOAA
GDD	Growing degree day is a measure of heat accumulation in the growing season, calculated by summing the difference between the daily temperature and the base temperature*.	NOAA Climate Data Online
SDD	Stress degree day is a measure of heat stress on crop plants in the growing season, calculated by summing the difference between the maximum daily temperature and 86 degrees Fahrenheit.	NOAA Climate Data Online
Loss ratio	Total indemnity divided by total premium for each peril	USDA Risk Management Agency
Crop Yield	Crop production bushel per acre	USAD National Agricultural Statistics Service
Crop Production	Total production of crops (winter wheat, corn, and sorghum) in 1,000 bushel	USAD National Agricultural Statistics Service

* The base temperatures are 40 degrees Fahrenheit for winter wheat, 45 degrees Fahrenheit for sorghum, and 50 degrees Fahrenheit for corn.

Table 3. Cloud seeding effects (Kansas sample)

	Weather variables			Crop loss ratio			Crop productivity		
	Hail frequency	Hail magnitude	Rainfall	Hail Loss ratio	Drought Loss ratio	Flooding Loss ratio	Wheat	Corn	Sorghum
Seed	-0.428 (1.126)	-0.098* (0.053)	0.259*** (0.078)	0.293 (0.257)	0.114 (0.132)	0.541*** (0.156)	-0.656 (1.516)	17.816*** (3.536)	-2.027 (2.406)
UWseed	2.548 (1.590)	0.095 (0.075)	-0.077 (0.110)	-0.184 (0.360)	0.199 (0.187)	0.111 (0.223)	-3.035 (2.226)	5.645 (5.053)	-9.983*** (3.361)
Wet	0.893*** (0.312)	0.017 (0.014)	0.808*** (0.022)	0.192** (0.076)	0.122*** (0.037)	0.237*** (0.042)	-0.686* (0.398)	0.435 (1.035)	3.738*** (0.765)
Dry	-1.790*** (0.454)	-0.059*** (0.022)	-0.502*** (0.031)	0.426*** (0.112)	0.652*** (0.053)	0.261*** (0.063)	-3.574*** (0.563)	-6.771*** (1.345)	-10.761*** (1.008)
GDD	0.0002 (0.0006)	-0.00001 (0.00002)	0.0001*** (0.00004)	0.0001 (0.0002)	-0.000001 (0.0003)	-0.0001 (0.0001)	-0.0004 (0.0005)	0.004*** (0.001)	0.004*** (0.001)
SDD	0.0002 (0.0002)	0.00007 (0.0001)	-0.0002 (0.0002)	-0.00001 (0.0006)	0.0003 (0.0003)	0.0005 (0.0003)	0.002 (0.003)	-0.039*** (0.007)	-0.034*** (0.005)
County Fixed-effects	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Time Fixed-effects	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
R-square									
Within	0.195	0.056	0.789	0.210	0.509	0.163	0.386	0.565	0.712
Between	0.029	0.004	0.527	0.161	0.040	0.019	0.067	0.001	0.226
Overall	0.136	0.051	0.565	0.197	0.482	0.135	0.327	0.208	0.599
Observations	1,842	1,842	1,835	1,842	1,800	1,774	1,615	1,426	1,193

*:10%, **:5%, ***:1% statistic significant.

Table 4. Cloud seeding effects (West Kansas sample)

Variable	Weather variables			Crop loss ratio			Crop productivity		
	Hail frequency	Hail magnitude	Rainfall	Hail Loss ratio	Drought Loss ratio	Flooding Loss ratio	Wheat	Corn	Sorghum
Seed	0.301 (1.096)	-0.034 (0.046)	0.015 (0.045)	0.237 (0.230)	0.027 (0.109)	0.504*** (0.184)	-0.707 (1.307)	8.499** (4.056)	-2.594 (2.456)
UWseed	3.150** (1.463)	0.117* (0.062)	-0.080 (0.061)	-0.165 (0.309)	0.127 (0.145)	0.062 (0.249)	-2.288 (1.805)	0.152 (5.471)	-10.191*** (3.267)
Wet	0.182 (0.437)	-0.026 (0.018)	0.196*** (0.018)	0.178* (0.094)	0.094* (0.044)	0.223*** (0.073)	0.389 (0.556)	2.701 (1.824)	4.610*** (1.057)
Dry	-1.438** (0.642)	0.012 (0.027)	-0.152*** (0.027)	0.063 (0.145)	0.502*** (0.068)	0.221* (0.118)	-2.281*** (0.777)	-8.128*** (2.312)	-10.146*** (1.492)
GDD	0.001 (0.001)	0.00003 (0.0001)	0.0002*** (0.0001)	-0.0002 (0.0003)	-0.0002 (0.0001)	-0.0002 (0.0002)	-0.003* (0.001)	0.005 (0.005)	-0.001 (0.003)
SDD	-0.0011 (0.003)	-0.0002 (0.0002)	-0.001*** (0.0002)	0.001 (0.001)	0.001* (0.0004)	0.001 (0.001)	0.007 (0.004)	-0.026* (0.014)	-0.011 (0.008)
County Fixed-effects	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Time Fixed-effects	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
R-square									
within	0.220	0.138	0.637	0.272	0.670	0.198	0.689	0.396	0.748
between	0.015	0.004	0.324	0.057	0.184	0.005	0.0004	0.117	0.127
Overall	0.173	0.114	0.241	0.239	0.612	0.160	0.539	0.147	0.538
Observations	638	638	641	617	615	587	498	454	466

*:10%, **:5%, ***:1% statistic significant.

Table 5. Net Benefit and Net Present Value of Counties Participating in the Cloud Seeding Program (2002–2016)

County	Number of years participating in program during 2002-2016	Net benefit (2002-2016) (real 2002 dollars)	Net Present Value	
			Real discount rate 3.1%	Real discount rate 3.9%
Finney	10	1,831,075	1,426,941	1,345,617
Gove	2	790,496	611,813	575,094
Grant	8	4,873,625	4,101,933	3,939,103
Gray	10	2,959,406	2,404,498	2,287,780
Greeley	6	6,189,554	4,649,501	4,331,813
Hamilton	11	5,506,160	4,586,679	4,393,534
Haskell	8	17,803,679	14,700,000	14,000,000
Kearny	13	2,015,673	1,382,509	1,252,628
Lane	14	-8,631,244	-7,137,036	-6,820,124
Scott	14	-2,517,396	-1,800,892	-1,657,309
Stanton	6	8,702,797	6,554,645	6,118,098
Stevens	2	4,375,014	3,237,275	3,001,360
Wallace	2	1,076,670	737,243	670,059
Wichita	11	7,220,984	5,869,599	5,571,474

Based year: 2002.

Table 6. Net present value of cloud seeding program in Kansas

	Net present value (2002-2016)	
	Real Discount Rates 3.1%	Real Discount Rates 3.9%
NPV (participating)	39,009,128	41,324,710
NPV (non-participating)	-28,031,183	-29,149,102
Overall	10,977,945	12,175,608

Appendix A. Theoretical Model of decision making of cloud seeding program

In this model, different levels of government compete to reduce their contributions while still maintaining the provision of the public good. Brien and Eger III's (2021) model builds on the work of Hettich and Winer (1984, 1988), who developed a normative model of tax structure to identify the motivations behind government decisions. Their model assumes that the aim of government officials is to maximize voter support, rather than acting as altruistic or omnipotent social planners. In this model, there are M county governments and one state government. County level elected officials seek to maximize utility specifically related to the jointly funded program. For a representative county j, there are N people living in the county.

County government official maximization problem:

$$Max\ U_j = \sum_{i=1}^{N} b_i\left(\alpha_j \cdot \overline{E_j}\right) - s\left(\alpha^u \bar{E}_j^u\right) - c_i(v_i)$$

$$\text{Subject to } \overline{E_j} = L_j + \bar{A}$$

$$\text{where } v_i = \frac{L_j}{N}$$

The local government elected official decides whether to participate in the program, with α as a binary variable (1 for participation, 0 otherwise). Once the county official decides to participate, he/she then determines the annual expenditure, $\bar{E}$, on the cloud seeding program. When the county adopts the program, it generates benefit for the residents. The political support to the county official can be expressed as $b_i(\alpha \cdot \bar{E})$, representing voter i's expected support for the county official due to the expenditure on cloud seeding program (Hettich and Winer, 1988). For example, spending on cloud seeding might reduce hail damage to farmer i's crops in the county, leading farmer i to support the county government official and thus increase the likelihood of success in the next election. Whilehe expenditures ($\bar{E}$) could in principle depend on other variables, for simplicity $\bar{E}$ is constant.

The political cost refers to the cost of levying taxes from taxpayers, represented by the function $c_i(v_i)$. In the function, v_i may represents not only the taxes paid by voter i, but also the broader deadweight loss associated with taxation (Hettich and Winer, 1988). The specific definition of v_i depends on the design of tax collection and the goals of the research.

Within the framework envisioned by Hettich and Winer (1988), all farmer production functions and taxable activities are included in the model, whereas Brien and Eger III's (2021) assume identical taxpayers, with each paying the same amount of tax for the project, represented as $v_i = \frac{L}{N}$. I follow Brien and Eger III's (2021) in this research because the focus is on the efficacy of cloud seeding program where local government contributions to covering the cost of cloud seeding are based on population size[26].

Expenditure on cloud seeding program is equal to the county government's contribution, denoted as L_j, plus, the contribution from the state government, denoted as $\overline{A}$.

One key difference in my model and that of Brien and Eger III's (2021) and Hettich and Winer (1988) is the function of $b_i()$. They assumed that $\partial b_i / \partial \overline{E} > 0$, which indicates that expenditure on the jointly funded program effectively corrects externalities. Although cloud seeding is intended to suppress hail damage, its effect might be zero or even negative. A key goal of this paper is to test the effectiveness of cloud seeding program. If the program results in a negative or zero impact on farmers in the county and leads to reduced political support, the outcome to the maximization problem would be to terminate the program, where $\alpha = 0$.

For a cloud seeding program, the political support in the county might be influenced by decisions made by upwind counties, i.e., a spatial spillover effect, represented by $s\left(\alpha^u \overline{E}_j^u\right)$. As mentioned in background section, one potential and controversial spillover effect of cloud seeding program is a reduction in rainfall in downwind areas. For example, farmer i might experience reduced rainfall and adverse impacts on flood and crop production, which could consequently lower the overall probability of voting for the current government. Here, I have not accounted for farmers' risk perceptions, but rather assume that farmers accurately attribute the rainfall reduction to the cloud seeding program rather than other potential causes, such as long-term climate trends.

The state government decides how much contribute to the cloud seeding program but does not control how the funds are distributed among the counties. This is represented as $A_j = \frac{A}{\sum_{j=1}^{M} \alpha_j}$. Therefore, the fewer counties that participate in the program, the more funding

[26] According to the *Council Grove Republican*, "County governments normally pay between $12,000 and $35,000 each year to help finance the weather effort, depending on population" (May 7, 1996, p. 2).

each participating county receives. However, reduced county participation may affect the total contribution from the state, which in turn could influence both the efficacy of the cloud seeding program and the potential support for it. For example, Kansas weather modification program officials have noted that too many storms with too few aircraft for cloud seeding missions can negatively impact the program's effectiveness.

Additionally, the state government may be unwilling to contribute to the program if the total contributions from local governments fall below a minimum service threshold, T. If the combined expenditure of all participating counties is less than T, the state government will contribute nothing, resulting in the termination of the jointly funded program. County officials focus solely on their own maximization problem and are unaware of the threshold set by the state government. The state government does not experience spillover effects. If the total political support resulting from funding the cloud seeding program is positive, the state government will pursue the political benefits, even if negative support exists from county j.

Appendix B. Farmers Production Model

Link to the model section, the government officers can levy tax from the residents. And based on Hettich and Winer (1984, 1988), the taxable activity can be derived from the production functions.

The cloud seeding program serves as a tool to mitigate hail damage, with the expectation that target areas experience increased agricultural productivity. However, the downwind effect may result in unintended impacts from the cloud seeding program. To offer a clearer assessment of these potential effects, consider the damage control model, as proposed by Lichtenberg and Zilberman (1986). In this approach, damage control agents, such as pest control and theft prevention, play a crucial role in preserving crop production and profitability.

Building on the work of Knowles and Skidmore (2021), who applied the damage control framework to the evaluation of cloud seeding programs as damage control agents for wheat and barley crops in North Dakota. Of direct relevance, Trilnick and Zilberman (2021) developed a structural model based on the damage control approach, which introduced microclimate engineering and sunlight reflection as damage control agents for pistachio yields in California.

In equation (B1), $Y_{it}(Z,W)$ represents the potential output function under weather conditions W, encompassing factors such as temperature, moisture, hail, etc. Z is a vector of production inputs, including fresh water, fertilizer, and labor, etc. $Y_{it}^{0}(Z)$ denotes the minimum crop output regardless of weather conditions, which is interpreted as the crop resiliency. For instance, it may account for a portion of the crops surviving after hail damage, and farmers might implement post-hail remedies to expedite the recovery of crops from damage. $G_{it}(W(c_{it}))$ is the damage or loss function, where $G_{it}(W\,(c_{it})) \in [0,1]$, and c_{it} indicates whether county *i* participated in cloud seeding program, the damage control of hail, in year *t* or not.

$$Y_{it}(Z,W) = Y_{it}^{0}(Z) + Y_{it}^{1}(Z)\{1 - [G_{it}(W_i(c_{it})]\} \tag{B1}$$

With this production function, farmers collectively in county i address the profit maximization problem outlined in equation (B2), where p_y, p_z, and p_c represent the prices of outputs, inputs, and participation in the cloud seeding program, respectively. For simplicity, here after denote $Y_{it}^{0}(Z)$ as equal to zero.

$$\max_{c_{it}} \quad \pi_{it} = p_y\{Y_{it}^{1}(Z)[1 - G_{it}(W_i(c_{it}))] - p_z Z - p_c c_{it} \tag{B2}$$

Assuming that farmers do not adjust inputs, Z, in conjunction with the decision of whether or not to participate in the cloud seeding program, the marginal effect of cloud seeding participation on profit is shown in equation (B3).

$$\frac{d\pi_{it}}{dc_{it}} = p_y Y_{it}^{1}(Z)(-\frac{\partial G_{it}}{\partial W_{it}}\frac{\partial W_{it}(c_{it})}{\partial c_{it}}) - p_c \tag{B3}$$

From equation (B3), the price and production are both positive terms. In general, weather conditions have a positive correlation with damage ($\frac{\partial G(W(.))}{\partial W}$>0). For instance, when more hailstorms occur in a year, there is a higher probability of crop damage. Moreover, as predicted by the beneficial competitiveness hypothesis (see section II), if the cloud seeding program effectively modifies adverse weather impacts such as reducing hailstorm frequency and magnitude, then $\frac{\partial W(c_{it})}{\partial c_{it}}$<0.

The damage abatement model should also account for spatial spillovers. For instance, Schneider et al. (2021) demonstrated that the timing of pest population control by one farmer can influence the efficacy of neighboring farmers' damage abatement inputs. In this study, I incorporate spatial spillovers into the model, where upwind county *j*'s decision regarding participation in the cloud seeding program influences county *i*'s weather, such as less rainfall or hailstorms. The revised maximization problem is illustrated in equation (B4), and the marginal effect of cloud seeding participation on profit is shown in equation (B5).

$$\max_{c_{it}} \quad \pi_{it} = p_y\{Y_{it}^1(Z)[1 - G_{it}(W_i(c_{it}, c_{jt}))] - p_z Z - p_c c_{it} \tag{B4}$$

$$\frac{d\pi_{it}}{dc_{it}} = p_y Y_{it}^1(Z)\left(-\frac{\partial G_{it}}{\partial W_{it}}\frac{\partial W_{it}(c_{it}, c_{jt})}{\partial c_{it}}\right) - p_c \tag{B5}$$

In the damage control model, the damage control agent may not directly enhance crop production; in some cases, it might even lead to a reduction in crop production (Lichtenberg and Zilberman, 1986). For instance, pesticides may not directly improve crop yield but can reduce pests, resulting in better plant growth. However, excessive pesticide application can harm crop plants. Similarly, if cloud seeding is effective and spillover effect is not considered, then $\frac{\partial W(c_{it})}{\partial c_{it}}$<0. However, if spillover effects are taken into consideration, the sign $\frac{\partial W_{it}(c_{it}, c_{jt})}{\partial c_{it}}$ is unknown; it could be either positive or negative. Based on this model, in the following section, the efficacy of cloud seeding and potential spillover effects are tested.

Appendix C. Propensity Score Matching

The data used in the preceding estimations included all counties in Kansas. To ensure robustness, the analysis is revised to include counties adjacent to Kansas in Colorado and Oklahoma, forming control and comparison groups, and utilized a logit model to predict the probability of counties adopting the cloud seeding program.

To identify treated counties for the analysis, we utilized The initial analysis focused solely on data from 2002, a year with a relatively high number of adopting counties compared to other years. In the logit model, variables such as downwind status, GDD, SDD, and the Palmer Z index were used to estimate the probability of adoption. The main difference arises from using the Palmer Z index rather than the Dry and Wet variables specified in the Data section (Section IV). This decision stemmed from the fact that 2002 experienced relatively dry conditions with lower moisture levels compared to normal conditions. Consequently, most of the Wet variables equated to zero, offering limited information due to the small sample size. Hence, we chose to utilize the Palmer Z index, the original variable employed in generating the Dry and Wet variables, in the logit model.

Based on the results of the logit model, we generated propensity scores for each county. Subsequently, we ranked each county by the propensity and matched one county that adopted the cloud seeding program to two counties that did not adopt the program but had similar propensity scores. In other words, within each matched group, these three counties exhibited similar tendencies to adopt the cloud seeding program. Consequently, we excluded counties that were not matched, as they might confound the results. After matching, 36 counties were included in the evaluation, primarily concentrated in the western part of Kansas, which is referred to as the West Kansas sample hereafter. In Figure C1, the counties shaded in orange indicate the West Kansas sample.

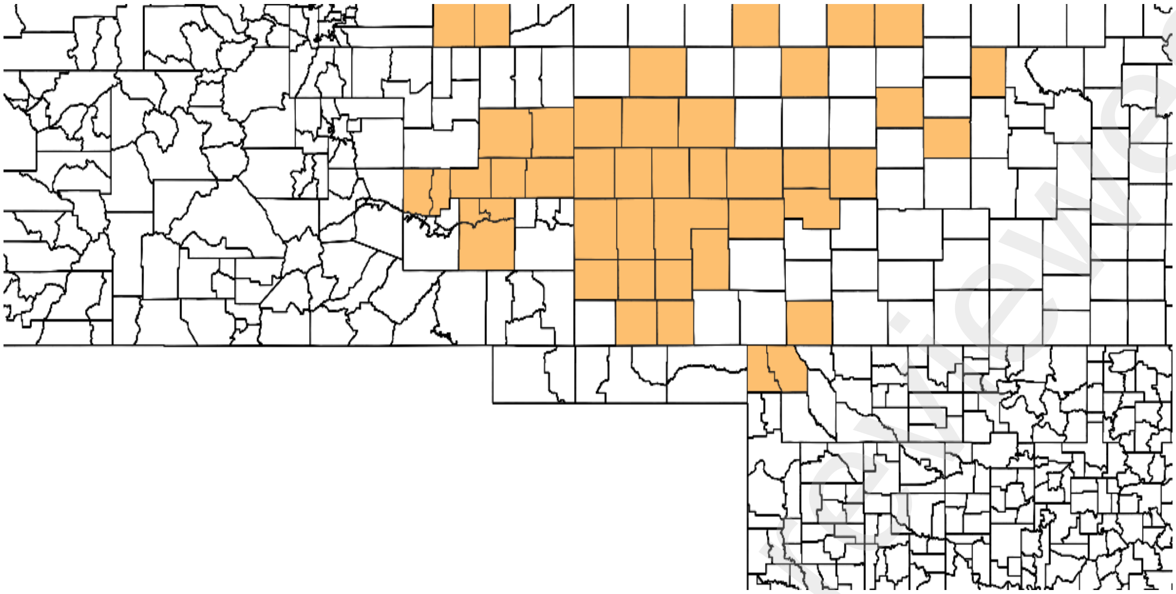


Figure C1. Kansas and West Kansas sample counties

Table C1. Crop damage indemnity (dollars per insured acre)

Variable	Total			Kansas			West Kansas		
	hail	drought	flooding	hail	drought	flooding	hail	drought	flooding
Seed	0.469 (0.560)	-1.680 (3.207)	1.282* (0.723)	0.332 (0.579)	-3.730 (3.269)	1.539* (0.787)	0.607 (0.725)	1.377 (2.608)	1.107 (0.786)
UWseed	0.092 (0.796)	6.048 (4.556)	0.173 (1.027)	0.001 (0.818)	5.073 (4.614)	0.243 (1.111)	0.253 (0.999)	6.366* (3.590)	0.241 (1.082)
Wet	0.146 (0.127)	-3.723*** (0.738)	2.264*** (0.164)	0.264* (0.161)	-3.373*** (0.925)	2.517*** (0.218)	0.330 (0.265)	-2.301** (0.953)	1.203*** (0.287)
Dry	-0.991*** (0.191)	12.306*** (1.097)	0.797*** (0.246)	-0.790*** (0.233)	16.235*** (1.320)	0.803** (0.317)	-0.979*** (0.374)	8.705*** (1.343)	0.449 (0405)
GDD	0.00008 (0.0003)	-0.001 (0.001)	-0.0006* (0.0003)	0.0001 (0.0002)	-0.002 (0.002)	-0.001** (0.0004)	-0.0001 (0.0006)	-0.004* (0.002)	0.0004 (0.0007)
SDD	0.001 (0.001)	0.015** (0.006)	0.001 (0.001)	0.001 (0.001)	0.022*** (0.007)	0.003 (0.002)	0.003 (0.002)	0.025*** (0.008)	-0.0008 (0.002)
County Fixed-effects	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Time Fixed-effects	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
R-square									
within	0.125	0.476	0.310	0.114	0.547	0.329	0.190	0.563	0.116
between	0.063	0.001	0.030	0.002	0.073	0.081	0.094	0.142	0.015
Overall	0.077	0.422	0.230	0.081	0.510	0.231	0.134	0.508	0.100

*:10%, **:5%, ***:1% statistic significant.

Table C2. Cloud seeding effects (Total sample)

Variable	Weather variables			Crop loss ratio			Crop productivity		
	frequency	magnitude	rainfall	hail	drought	flooding	Wheat	Corn	Sorghum
Seed	-0.280 (1.161)	-0.047 (0.044)	0.056 (0.052)	0.268 (0.269)	0.159 (0.134)	0.534*** (0.163)	-0.700 (1.505)	16.215*** (3.925)	-3.440 (2.499)
UWseed	2.778* (1.634)	0.102* (0.062)	-0.085 (0.074)	-0.102 (0.381)	0.221 (0.189)	0.109 (0.235)	-2.948 (2.210)	4.413 (5.631)	-11.021*** (3.521)
Wet	0.340 (0.263)	-0.001 (0.009)	0.294*** (0.012)	0.153** (0.062)	0.092*** (0.031)	0.229*** (0.037)	-1.132*** (0.373)	1.239 (0.991)	3.006*** (0.666)
Dry	-1.670*** (0.398)	-0.013 (0.015)	-0.132*** (0.018)	0.353*** (0.097)	0.577*** (0.048)	0.203*** (0.058)	-3.524*** (0.520)	-7.378*** (1.312)	-9.980*** (0.910)
GDD	0.0003 (0.0005)	0.00003 (0.00002)	0.0001*** (0.00002)	0.0002 (0.0001)	0.00003 (0.00006)	-0.0001 (0.00007)	-0.0005 (0.0005)	0.005*** (0.002)	0.004*** (0.001)
SDD	0.0009 (0.0021)	-0.0001 (0.0001)	-0.0003*** (0.0001)	-0.0005 (0.0005)	0.00006 (0.0003)	0.0006* (0.0003)	0.003 (0.003)	-0.035*** (0.007)	-0.031*** (0.005)
County Fixed-effects	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Time Fixed-effects	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
R-square									
within	0.164	0.103	0.599	0.130	0.454	0.158	0.390	0.457	0.651
between	0.0001	0.044	0.493	0.015	0.076	0.011	0.093	0.003	0.123
Overall	0.095	0.081	0.101	0.099	0.418	0.132	0.306	0.137	0.477
Observations	2,259	2,259	2,319	2,196	2,154	2,128	1,762	1,665	1,468

*:10%, **:5%, ***:1% statistic significant.

Appendix D.

Table D1. Net Benefit and Net Present Value of Counties Participating in the Cloud Seeding Program (2002–2016)

County	Number of years participating in program during 2002-2016	Net benefit (2002-2016) (real 2002 dollars)	Net Present Value	
			Discount rate 3.1%	Discount rate 3.9%
Finney	10	22,385,099	19,300,000	18,600,000
Gove	2	1,459,277	1,065,190	984,491
Grant	8	11,625,797	9,338,420	8,858,088
Gray	10	19,057,089	15,300,000	14,500,000
Greeley	6	11,344,974	8,027,018	7,364,672
Hamilton	11	10,271,209	8,280,079	7,855,697
Haskell	8	36,540,874	29,600,000	28,200,000
Kearny	13	12,153,677	10,000,000	9,580,517
Lane	14	-6,337,185	-5,135,528	-4,883,257
Scott	14	9,101,877	8,026,396	7,793,650
Stanton	6	15,862,281	12,500,000	11,800,000
Stevens	2	7,954,878	6,330,899	5,975,491
Wallace	2	1,976,468	1,597,694	1,515,924
Wichita	11	17,683,923	14,700,000	14,000,000

*Price is average price of each month of grain crops. The production gain and loss are based on the estimation of Table 3.

Table D2. Net Present Value of Cloud Seeding Program in Kansas

	Net present value (2002-2016)	
Real Discount Rates	3.1%	3.9%
NPV (participating)	-28,031,183	-29,149,102
NPV (non-participating)	39,009,128	41,324,710
Overall	10,977,945	12,175,608