

Article

Evaluation of Aircraft Cloud Seeding for Ecological Restoration in the Shiyang River Basin Using Remote Sensing

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Abstract

The use of aircraft for cloud seeding to enhance rainfall serves as an effective meteorological intervention and plays a vital role in ensuring ecological security within the context of the low-altitude economy. This study utilized ground-based precipitation observations from the Shiyang River Basin, in conjunction with Landsat satellite remote sensing imagery (2000–2024), regional historical regression, vegetation index retrieval, and spectral mixture analysis, to evaluate the effectiveness of aircraft-based cloud seeding for enhancing rainfall. The normalized difference vegetation index and the fraction of vegetation cover were calculated to examine the spatiotemporal dynamics and growth patterns of surface vegetation before and after the implementation of this rainfall enhancement measure, thus offering a quantitative assessment of the ecological restoration effect in the Shiyang River Basin. A novel application of cloud-seeding technology for ecological recovery has been developed. It provides one of the first quantitative assessments of aircraft-based cloud seeding in inland river basins of China, linking meteorological intervention directly to measurable ecological restoration outcomes. The findings indicate that: (1) Aircraft-based cloud seeding for rainfall enhancement has yielded significant results, with an average relative precipitation increase of 20.8% ($p < 0.1\%$) in the operational area; (2) Following the commencement of this rainfall enhancement practice in 2010, normalized difference vegetation index and fraction of vegetation cover values within the study area have shown a marked increase, with the percentage of regions with low vegetation coverage declining from 30.36% to 25.21%; and (3) Since the implementation of this measure in 2010, vegetation conditions in the Shiyang River Basin have generally stabilized, demonstrating substantial improvement and a reduction in degradation. The percentage of regions classified as improved or slightly improved increased significantly, from 14.20% before the implementation of this measure to 36.24%, indicating a transition in the vegetation ecosystem from localized enhancement to overall improvement. These results demonstrate that ecological restoration efforts in the Shiyang River Basin have shown considerable improvement after the introduction of aircraft-based cloud-seeding operations, resulting in significant increases in vegetation coverage throughout extensive regions of the basin. The research connects scientific results to policy and management, suggesting that low-altitude economy-based cloud seeding can play a key role in water resource management, ecological stability, and climate resilience.



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Keywords: Shiyang River Basin; low-altitude economy; fraction of vegetation cover; remote sensing; ecological restoration

1. Introduction

China is one of the countries most affected by natural disasters globally, with drought-related water shortages becoming a significant concern that hinders the swift economic development of arid and semi-arid areas [1]. The impact of climate change on the vegetation growth environment in arid inland river basins has been significant, as indicated by changes in precipitation distribution. Arid inland river basins have emerged as regions most severely affected by ecological degradation in China. Consequently, the implementation of cloud-seeding measures is considered the most effective approach to reducing and mitigating ecological degradation [2]. Recently, the use of general aviation aircraft for cloud seeding to enhance rainfall has emerged as a significant aspect of the development of China's low-altitude economy [3]. Compared with conventional ground-based, fixed-point seeding methods, aircraft, which possess large payload capacity, long flight endurance, and high operational adaptability, can substantially improve both the efficiency and precision of artificial cloud seeding for rainfall enhancement [4]. General aviation aircraft, characterized by strong maneuverability, uniform dispersal of seeding agents, and extensive coverage, are able to deliver agents directly to the most favorable locations within cloud systems [5]. This makes them particularly suitable for large-scale precipitation cloud systems, where they provide advantages that are difficult for ground-based operations to achieve [6]. At present, the use of aircraft for cloud seeding aimed at rainfall enhancement is not only an effective form of meteorological intervention but also an important representation of how the low-altitude economy contributes to public welfare, safeguards ecological security, and promotes industrial innovation [7].

The Shiyang River Basin, located in the arid and semi-arid regions of northwestern China, serves as a key inland river basin that is essential for maintaining ecosystem stability [8]. This stability has important implications for global climate change and the hydrological cycle [9]. Nonetheless, due to the simultaneous effects of climate change and human activity, the basin has experienced significant ecological degradation [10]. Specifically, the upper reaches have experienced a continuous decline in snow and ice resources, reduced river runoff, and diminished water-retention capacity of vegetation; the middle reaches face excessive agricultural water consumption; and the lower reaches are characterized by shrinking natural oases and intensified desertification, creating a critical situation in which the Tengger and Badain Jaran deserts are approaching convergence [11]. To address the problem of water scarcity and restore the vegetation ecosystem in the inland river basins of the Qilian Mountains, local governments and meteorological departments have implemented a series of measures that integrate ecological with cloud seeding operations oriented toward rainfall enhancement [12–14]. Since 1995, the local government has conducted targeted cloud seeding operations in the mountainous upper reaches of the Shiyang River, deploying ground-based silver iodide generators and other techniques. Since 2010, the application of aircraft-based rainfall enhancement cloud seeding technology to actively utilize atmospheric water resources has become one of the primary approaches to vegetation ecosystem restoration in the inland river basins of the Qilian Mountains [15]. These measures are designed to increase precipitation, improve soil moisture conditions, and promote vegetation growth, thereby facilitating ecological restoration in the Shiyang River Basin.

The potential of cloud seeding to address water scarcity and support ecological or agricultural systems is increasingly recognized in diverse climatic regions worldwide. The Karnataka Cloud Seeding Program reports an average increase in rainfall of 27.9% attributable to the seeding operations in Karnataka, India [16]. In the Republic of Moldova, a country facing intensified drought periods, Valjarević et al. utilized 30 years of satellite data (1990–2020) to demonstrate a 15% increase in cloudiness and to identify areas with high

potential for obtaining additional water through cloud seeding [17]. Previous research has shown that ecological restoration initiatives utilizing aircraft-based cloud seeding for the enhancement of rainfall and snow are among the most effective methods for addressing and reversing ecological degradation. Furthermore, these initiatives represent a long-term and evolving process [18,19]. The time required for restoration is closely linked to the degree of degradation, with recovery taking 3–10 years for slightly degraded areas, 10–20 years for moderately degraded areas, 50–100 years for severely degraded areas, and more than 200 years for areas experiencing extreme degradation [20]. Wen et al. [21], focusing on the cloud water resources in the Sanjiangyuan region on the Qinghai–Tibet Plateau, examined the rainfall enhancement potential of cloud seeding and its ecological impacts. Their results indicated that precipitation enhancement could alleviate water shortages in Sanjiangyuan, enlarge lake surface areas, improve grassland coverage, and increase river runoff at the sources. Ma et al. [22] reported that artificial rainfall enhancement in the Maqu region of the Gannan Tibetan Autonomous Prefecture, located in the south of Gansu province, had beneficial effects on grassland productivity and vegetation coverage, with average grassland yield increasing by more than 20%. Yuan et al. [23], through investigations of rainfall enhancement operations in the Qilian Mountains based on cloud seeding, found that these operations significantly promoted vegetation restoration in the Shiyang River Basin, with the region exhibiting an increasing trend in runoff, mean vegetation index, and mean vegetation coverage. Guo et al. [24] observed that during rainfall enhancement cloud seeding operations in the Shiyang River Basin, the operational areas experience clear increases in runoff and noticeable vegetation restoration effects, with the southeastern upper reaches showing the most significant improvements. Chen et al. [25], applying four statistical methods to analyze rainfall enhancement operations in the Shiyang River Basin, concluded that operations conducted in the eastern Hexi Corridor achieved significant results, effectively enhancing vegetation growth conditions in inland river basins.

Nevertheless, existing research has mainly concentrated on assessing the effects of expanded operational sites and increasing the volume of cloud seeding within the Shiyang River Basin. The use of large-scale, long-term remote sensing data to perform quantitative evaluations of vegetation growth across the entire basin before and after the introduction of aircraft-based rainfall enhancement measures remains limited. Although nearly 15 years have passed since the implementation of this measure by local governments and meteorological departments, quantitative analysis employing long-term time series data to determine its effect on vegetation restoration within the basin is still lacking. The quantitative evaluation of cloud seeding technology in China's inland river basins, through the effective integration of ground-based precipitation measurements and high-resolution remote sensing data, still requires further improvement. Moreover, further research is necessary to establish a direct link between meteorological interventions and measurable ecological restoration outcomes.

The present study combines ground-based precipitation observations with high-resolution, long-term satellite remote sensing imagery from the Shiyang River Basin. It also incorporates regional historical regression, vegetation index retrieval, and spectral mixture analysis (SMA) to analyze the significance of rainfall enhancement effects resulting from aircraft-based cloud seeding. Furthermore, the study estimates two vegetation parameters, namely the normalized difference vegetation index (NDVI) and fraction of vegetation cover (FVC), to analyze the spatiotemporal dynamics and growth trends of surface vegetation before and after the implementation of the rainfall enhancement measure. This provides a quantitative evaluation of the ecological restoration effects in the Shiyang River Basin. This paper aims to completely assess the ecological and environmental conditions along with their developmental trends in the region. It provides a scientific basis for the protection

of vegetation and the management of water resources in inland river basins of arid areas. Additionally, in the context of climate change, it offers fresh perspectives on how the low-altitude economy can contribute to public welfare and ensure ecological security.

2. Study Area

The Shiyang River Basin is situated in the Hexi Corridor area of northwestern China, at the transitional convergence zone of the Loess Plateau, the Tibetan Plateau, and the Inner Mongolia Plateau. This serves as a crucial link for the protection of economic, cultural, and ecological interests, along with facilitating exchanges and collaboration between China and nations in Central Asia and Europe. The basin covers an area of roughly 41,600 km², spanning the coordinates 101°41'–104°16' E and 36°29'–39°27' N (Figure 1). The region comprises three primary geomorphological units: the southern Qilian Mountains, the central corridor plain, and the northern low mountainous, hilly, and desert areas. The area experiences annual precipitation levels between 150 and 300 mm, while annual evaporation rates range from 1300 to 2600 mm. Desert regions constitute 68% of the basin, while vegetation accounts for merely 32%, highlighting the unique features of inland river basins in arid areas [26]. The basin exhibits low annual precipitation, high evaporation rates, and significant temperature differences between day and night, as well as between summer and winter. Precipitation is highly uneven, with over 60% of the annual total occurring between June and September, primarily in the form of short-duration, high-intensity convective rainfall events in the Qilian Mountains [2]. The primary sources of water supply for the middle and lower reaches of the Shiyang River Basin are rainfall and ice-snow meltwater originating from the Qilian Mountains in the upper reaches.

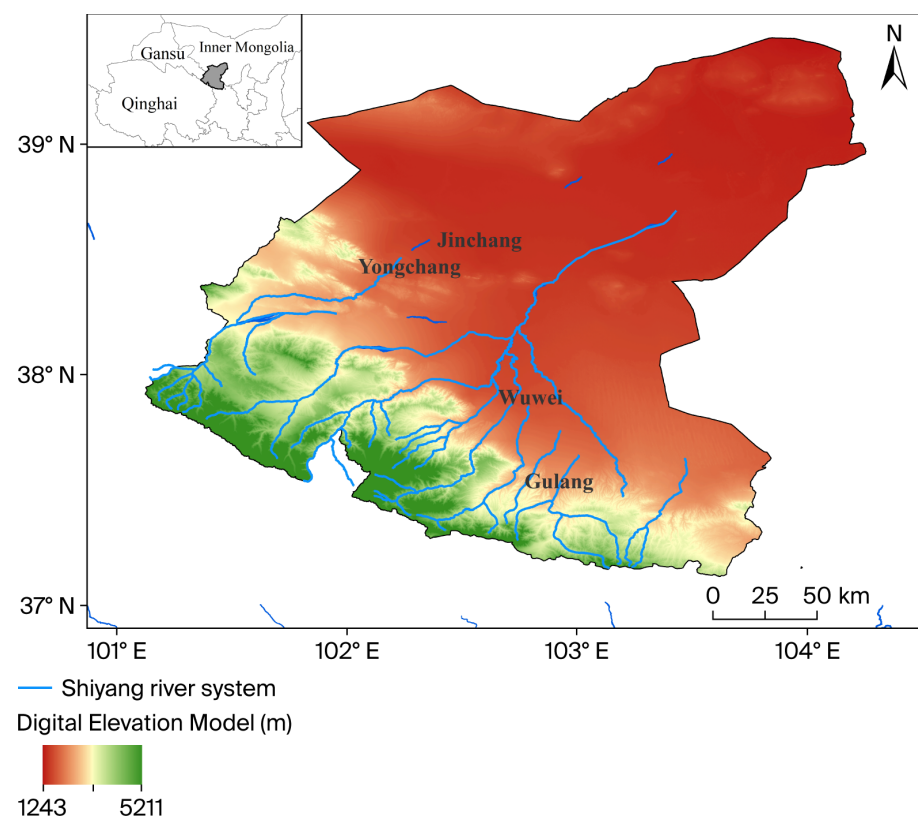


Figure 1. A schematic representation of the Shiyang River Basin, illustrating the river system linked to the region.

3. Materials and Methods

3.1. Precipitation Data

Precipitation data used in this study were obtained from the China Meteorological Data Service Center (<http://data.cma.cn>), covering the period from 1990 to 2024 for three meteorological stations: Wuwei, Gulang, and Yongchang. The three meteorological stations were selected based on the paramount need for long-term, continuous, and high-quality data to ensure the robustness of our 35-year trend analysis (1990–2024). Consistency checks were conducted on the timing and climatic threshold values of precipitation records based on the data quality control identifier to ensure data quality and integrity. The dataset consists of daily precipitation records measured in units of 0.1 mm, which were aggregated into monthly totals. Since both aircraft-based rainfall enhancement operations and vegetation growth predominantly occur from April to October, precipitation data for this time frame were selected for subsequent statistical analyses Table 1.

Table 1. Monthly average precipitation (in mm) at Wuwei station, Gulang station, and Yongchang station from 1990–2024.

Stations	Months											
	January	February	March	April	May	June	July	August	September	October	November	December
Wuwei	2.2	2.2	8.5	10.7	20.8	14.4	8.0	10.4	32.6	23.2	2.0	2.8
Gulang	5.1	6.6	30.4	42.5	60.2	37.6	31.8	21.3	53.7	37.3	5.1	5.5
Yongchang	2.1	2.9	13.8	20.1	15.9	23.0	17.5	30.7	47.4	8.4	1.0	2.1

3.2. Remote Sensing Data

Remote sensing imagery from Landsat TM/ETM/OLI for the study area was obtained via the Google Earth Engine platform, covering the period from April to October between 2000 and 2024. First, images exhibiting cloud cover of 10% or less were chosen, followed by preprocessing steps such as radiometric calibration, geometric correction, and projection transformation. Next, using QA pixel files as references, we masked invalid pixels such as clouds and cloud shadows within each image. Subsequently, based on QA radiation files, we flagged and removed pixels affected by radiometric saturation in the blue, green, red, and near-infrared bands. Finally, surface reflectance data was generated. The processed datasets were then utilized to compute vegetation parameters, including NDVI and FVC, for spatiotemporal analysis throughout the study regions as shown in Table 2.

Table 2. Overview of selected remote sensing datasets.

Satellite Series	Sensor	Spatial Resolution (m)	Datasets	Selected Time	Number of Images
Landsat5	TM	30	LANDSAT/LC05/C02/T1_L2	1 April 2000–31 October 2012	8
Landsat7	ETM+	30	LANDSAT/LC07/C02/T1_L2	1 April 2012–31 October 2013	7
Landsat8	OLI	30	LANDSAT/LC08/C02/T1_L2	1 April 2013–31 October 2024	10

3.3. Methods for Evaluating the Rainfall Enhancement and Ecological Restoration Effects of Aircraft-Based Cloud Seeding

The evaluation first involved testing the statistical significance of rainfall enhancement effects by comparing cloud seeding operation areas with control areas, using ground-based precipitation observations in conjunction with regional historical regression. Based on this foundation, NDVI and FVC were estimated and monitored through the use of 30 m resolution Landsat satellite data combined with vegetation index retrieval and SMA. Finally, the ecological restoration effect in the Shiyang River Basin was quantitatively assessed by analyzing the spatiotemporal trends of FVC across two periods, namely before and after the implementation of rainfall enhancement-oriented cloud seeding measures (Figure 2).

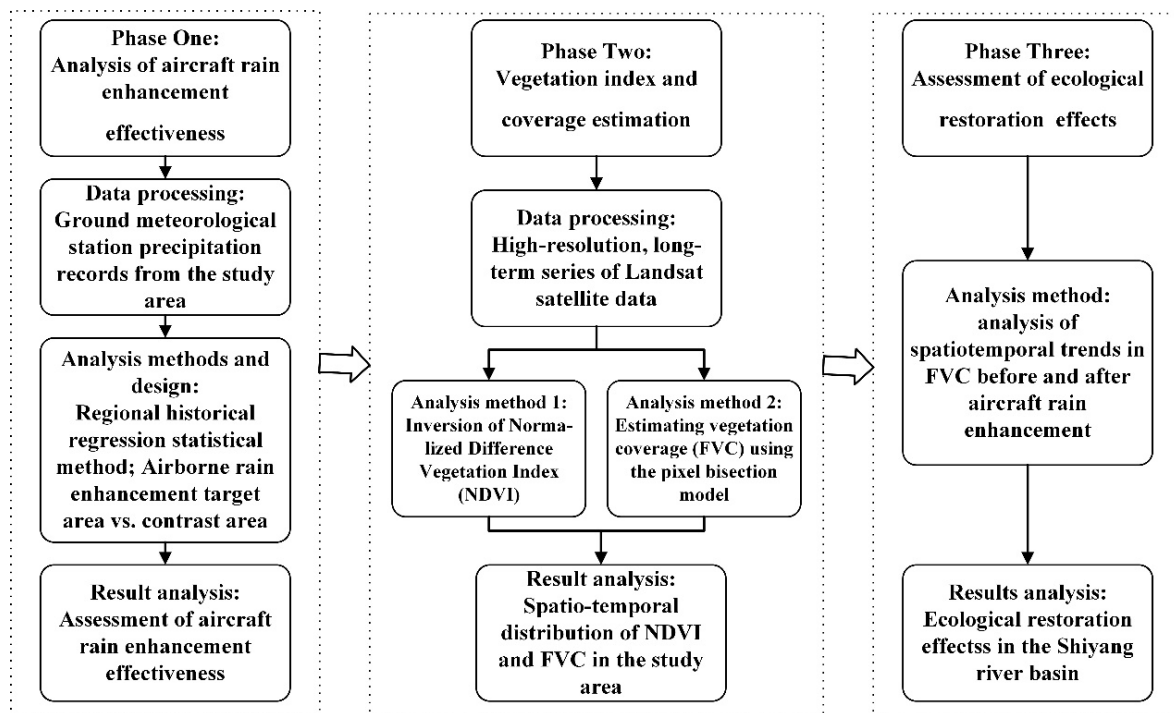


Figure 2. Flowchart for verifying aircraft rain enhancement effectiveness and assessing ecological restoration effects.

3.3.1. Statistical Testing of Rainfall Enhancement Effect

Prior research has shown that the regional historical regression and statistical testing method is an effective technique that has received broad acceptance from the global meteorological community [27]. This method is based on the analysis of historical precipitation correlations between the target area and the control area, which facilitates precise estimation of natural precipitation in the target area during designated operational periods. The estimated value is subsequently compared with the actual observed precipitation in the target area. The difference between these two values indicates the actual change in precipitation, thereby illustrating the rainfall enhancement effect of weather modification operations. This approach offers robust statistical testing capabilities while laying a firm scientific groundwork for assessing the efficacy of weather modification initiatives. The evaluation procedure consists of the subsequent steps:

- (1) Delineate appropriate target and control areas.
- (2) Perform normal transformation and normality testing on the historical precipitation data from both the target and control areas, with the Kolmogorov–Smirnov goodness-of-fit test used for assessing normality.
- (3) Conduct a significance test of the correlation coefficient using the *t*-test, as expressed in Equation (1):

$$t_{\alpha} = r \sqrt{\frac{v}{1 - r^2}}, \quad v = n - 2. \quad (1)$$

- (4) Establish a simple linear regression equation, and test its significance using the F-test, as shown in Equation (2):

$$F = \frac{b^2 S_x^2}{v_2} \frac{v_1}{S_y^2 - b^2 S_x^2}, \quad v_1 = n - 1, \quad v_2 = 1. \quad (2)$$

- (5) Calculate the rainfall enhancement effect. The normally transformed precipitation data from the control area during the operational period are substituted into the

regression equation to estimate the precipitation in the target area, which represents the natural precipitation (expected value) [28]. Comparison of this expected value with the actual observed precipitation in the target area after rainfall enhancement operations provides the absolute rainfall enhancement amount (Q_{SR}) and the relative rainfall enhancement (R_{SR}), which are calculated according to Equations (3) and (4):

$$Q_{SR} = Y_2 - Y_1, \quad (3)$$

$$R_{SR} = \left(\frac{Y_2}{Y_1} - 1 \right) \times 100\%, \quad (4)$$

where Y_1 denotes the expected precipitation in the target area, obtained by substituting the observed precipitation in the control area during the operational period (Y_2) into the regression equation.

- (6) Test the significance of the results. The t -test is employed to evaluate the statistical significance of the calculated rainfall enhancement effect, as given in Equation (5):

$$t = \frac{\bar{y}_k - \bar{y}'_k}{\sqrt{\frac{1-r^2}{n-2} \sum_{i=1}^n (y_i - \bar{y}_n) \left[\frac{1}{k} + \frac{1}{n} + \frac{(\bar{x}_k - \bar{x}_n)^2}{\sum_{i=1}^n (x_i - \bar{x}_n)^2} \right]}}, \quad (5)$$

where $\bar{y}_k$ and $\bar{y}'_k$ represent the mean observed precipitation and the mean estimated natural precipitation in the operational area, respectively; r denotes the correlation coefficient of historical monthly precipitation between the control and the operational area; k is the number of operational samples; and n corresponds to the number of historical samples. Variables x_i and y_i denote the historical monthly precipitation in the control and the operational area, respectively; $\bar{x}_k$ represent the mean regional precipitation in the control area during the operational period; $\bar{x}_n$ and $\bar{y}_n$ indicates the mean precipitation in the operational and control areas during the historical period, respectively. All of these precipitation data are normally transformed prior to analysis.

3.3.2. Identification of Target and Control Areas

In this study, Wuwei County and Gulang County were selected as the operational target area, while Yongchang County was designated as the control area (Figure 3).

The identification of target and control areas adhered to established principles commonly utilized in prior studies, with particular considerations outlined as follows: The control areas are located in the upwind direction of the target areas. This is to prevent potential downstream effects from artificial precipitation enhancement operations from influencing the natural precipitation conditions in the control areas, thereby ensuring the independence of precipitation data collected there. At 500 hPa, the dominant wind direction over the Shiyang River Basin is northwesterly, which is typically considered indicative of the prevailing atmospheric circulation patterns. The identified characteristics enable the prediction and management of rainfall enhancement outcomes resulting from cloud seeding activities. Consequently, Yongchang County, designated as the control area, was strategically located upwind of the operational area to mitigate any potential effects from cloud seeding operations. Additionally, both the target and control areas exhibit comparable characteristics regarding geographical location, climatic conditions, and meteorological background, which ensures robust comparability in critical indicators such as precipitation. The topography of both the target and control areas transitions from the Qilian Mountains to the northern corridor plains, with overlapping elevation ranges (Figure 1). These topographical conditions exert comparable influences on air uplift mechanisms and precipitation formation processes. Historical meteorological data from

the two stations indicate similar levels of annual precipitation and comparable variability patterns across the two areas (Table 1). Furthermore, an analysis of flight path data from aircraft-based rainfall enhancement cloud seeding operations conducted between 2010 and 2024 (refer to Figure 3) indicates that the majority of these operations were concentrated in Wuwei County, Gulang County, and the southern Qilian Mountains, while Yongchang County experienced minimal impact from these activities.

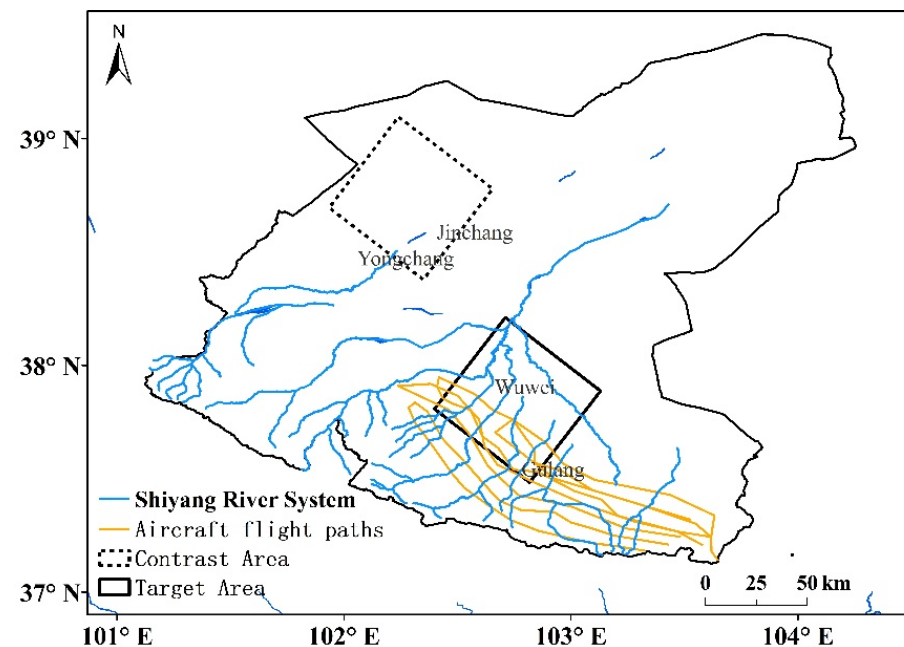


Figure 3. The designated target and control area for the verification of aircraft-based rainfall enhancement within the Shiyang River Basin.

In summary, this study has comprehensively considered multiple factors, including atmospheric dynamics orientation, underlying surface environment, and historical rainfall data in the selection of target and control areas.

3.3.3. Parameters and Methods for Evaluating the Ecological Restoration Effects of Rainfall Enhancement-Oriented Cloud Seeding Operations

(1) Remote Sensing-based NDVI Retrieval

NDVI is a vegetation index derived from remote sensing data, which is an indicator of vegetation growth status and vegetation coverage. It is calculated as follows:

$$I = \frac{N - R}{N + R} \quad (6)$$

where I represents NDVI, N denotes the reflectance of the near-infrared (NIR) band in the Landsat imagery, and R denotes the reflectance of the red band. NDVI values range from -1 to 1 and are widely used to represent vegetation coverage and growth status, with higher values corresponding to denser vegetation.

(2) Spectral Mixture Analysis

SMA is a method used to analyze multispectral reflectance data from remote sensing imagery [23]. Each pixel observed by the sensor is considered a mixed pixel S , comprising a vegetation component S_a , and a soil component S_b :

$$S = S_a + S_b. \quad (7)$$

Each mixed pixel is assumed to consist only of vegetation and bare soil, with the FVC denoted as F_{VC} , and the fraction of bare soil as $1 - F_{VC}$. If the reflectance of pure vegetation pixels is S_{veg} and that of pure soil pixels is S_{soil} , then:

$$S_a = F_{VC} \times S_{veg}, \quad (8)$$

$$S_b = (1 - F_{VC}) \times S_{soil}. \quad (9)$$

Therefore,

$$F_{VC} = \frac{S - S_{soil}}{S_{veg} - S_{soil}}. \quad (10)$$

3.3.4. Remote Sensing-Based Retrieval and Classification of FVC

FVC represents the proportion of the land surface covered by vegetation within a given area and serves as a comprehensive quantitative indicator of vegetation cover status. Among the available methods for FVC retrieval, the vegetation index-based approach is one of the most widely applied, estimating FVC through vegetation indices from remote sensing data.

Based on Equation (10) and the principles of SMA, FVC can be expressed as:

$$F_{VC} = \frac{I - I_{soil}}{I_{veg} - I_{soil}}, \quad (11)$$

where I_{veg} denotes the NDVI value for areas of full vegetation cover, and I_{soil} denotes the NDVI value for bare soil. In practice, according to the cumulative distribution function of NDVI, the NDVI values corresponding to cumulative distribution function values of 0.5% and 95% are typically selected as I_{veg} and I_{soil} , respectively.

In this study, the FVC of the Shiyang River Basin was categorized into five classes: $FVC < 5\%$ representing areas with low vegetation coverage, $5\% \leq FVC < 25\%$ for moderately low coverage, $25\% \leq FVC < 50\%$ for moderate coverage, $50\% \leq FVC < 75\%$ for moderately high coverage, and $FVC \geq 75\%$ for high coverage.

For the period between 2000 and 2024, FVC data were extracted at 4 to 5-year intervals for the years 2000, 2005, 2010, 2015, 2020, and 2024. Based on these classification criteria, the area proportions of each FVC level were calculated, and the spatiotemporal variations in FVC across the long-term time series in the study area were analyzed.

3.3.5. Trend Analysis of FVC

To characterize the temporal trends of FVC in the study area with higher accuracy, the least squares method was applied, with year as the independent variable and FVC as the dependent variable. This approach determines the regression line by minimizing the sum of squared differences between the observed values and the fitted values, thereby yielding the best-fit line. The Mann–Kendall test was subsequently applied to assess statistical significance, followed by the use of Sen's slope estimator to obtain a robust quantification of the magnitude of change. From this regression, the slope (S) of FVC in the study area was derived. These approaches are widely adopted in remote sensing-based time series analysis and ensure that our findings on vegetation dynamics are both statistically sound and reliable [29]. The slope provides a quantitative measure of the temporal trend of FVC and is expressed as follows:

$$S = \frac{n \times \sum_{i=1}^n \times F_i - \sum_{i=1}^n i \sum_{i=1}^n F_i}{n \times \sum_{i=1}^n i^2 - (\sum_{i=1}^n i)^2}, \quad (12)$$

where S represents the slope of FVC change, n denotes the number of years, and F_i indicates the FVC in the i -th year.

Based on the temporal trends of FVC, the Mann–Kendall test at a 0.1 confidence level was applied to classify the evolution of FVC into five categories:

- (1) Deterioration: FVC decreases significantly, indicating severe vegetation degradation or substantial ecological damage.
- (2) Mild deterioration: FVC decreases slightly, suggesting potential degradation or moderate disturbance of vegetation.
- (3) Stabilization: FVC remains generally stable without a significant upward or downward trend.
- (4) Mild improvement: FVC increases slightly, implying moderate vegetation recovery or relatively slow ecological improvement.
- (5) Improvement: FVC increases significantly, reflecting good vegetation growth or rapid ecological recovery.

4. Results

4.1. Analysis of the Rainfall Enhancement Effects of Cloud Seeding

Table 3 illustrates that from April to October in the years 2010 to 2024, the absolute rainfall enhancement varied between 5.4 mm and 6.9 mm, whereas the relative rainfall enhancement fluctuated from 12.3% to 47.2%. The average relative increase in rainfall was 20.8%, accompanied by an average absolute monthly rainfall increase of 6.1 mm. The total absolute rainfall increase from April to October amounted to 42.9 mm, while the total rainfall increase resulting from aircraft-based cloud seeding over the last 15 years in the Shiyang River Basin was 643.5 mm. The effects of rainfall enhancement exhibited clear variations across different seasons. The enhancement of artificial rainfall during the spring months of April to May and the autumn months of September to October was significantly greater compared to the summer months of July to August. April and October demonstrated the most significant effects, showing absolute rainfall increases of 6.8 mm and 6.9 mm, along with mean relative rainfall enhancements of 45.2% and 27.7%, respectively. In comparison, July exhibited the least impact, showing an absolute increase in rainfall of merely 5.4 mm and a relative increase of 12.3%. The results indicate that in times of relatively low natural precipitation, specifically in April and October, artificial intervention measures have a more pronounced marginal effect in enhancing precipitation.

Table 3. Linear fitting regression equation and significance test.

Months	Fitting Equations	Q _{SR} (mm)	R _{SR} (%)	<i>t</i> -Test	Significance ($p < 0.1\%$)
April	$y = 1.16 + 0.636x$	6.8	45.2	7.43	*
May	$y = 0.738 + 0.829x$	5.9	15.4	2.73	*
June	$y = 0.676 + 0.797x$	5.8	13.7	1.62	*
July	$y = 1.373 + 0.598x$	5.4	12.3	1.67	*
August	$y = 0.971 + 0.777x$	5.6	15.1	1.64	*
September	$y = 0.932 + 0.761x$	6.5	16.2	2.44	*
October	$y = 0.842 + 0.762x$	6.9	27.7	5.02	*

Note: Significance levels: * for $p < 0.1\%$.

4.2. Evaluation of Vegetation Index Effects

Using Landsat satellite remote sensing data from April to October for the period 2000–2024, the mean growing-season NDVI of the Shiyang River Basin was calculated (Figure 4). The results show that during this period, the NDVI ranged from 0.132 to 0.223, with an increasing trend of 4.3×10^{-3} per year. Before the implementation of artificial

rainfall enhancement operations (prior to 2007), intensive human activities had reduced ecological water use and caused a persistent decline in groundwater levels, leading to a low NDVI value of only 0.132 in 2006. From 2000 to 2006, vegetation in the basin generally exhibited a state of degradation. In 2007, ecological restoration measures were introduced in the basin, after which NDVI began to recover. In particular, following the initiation of aircraft-based cloud seeding operations in 2010, NDVI increased significantly, reaching a peak of 0.251 in 2024. Compared with the pre-2010 baseline value of 0.132, NDVI rose by 0.119 after the start of the operations. These results demonstrate that aircraft-based cloud seeding operations for rainfall enhancement have played a key role in promoting vegetation restoration in the Shiyang River Basin.

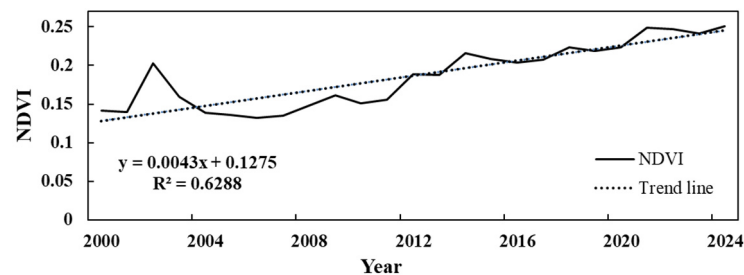


Figure 4. Average vegetation index during the growing season from 2000–2004.

4.3. Evaluation of FVC Effects

As illustrated by the area proportions of different FVC levels (Figure 5), low and moderately low vegetation coverage accounted for 58.09%, 61.01%, and 63.01% of the total study area in 2000, 2005, and 2010, respectively, while moderate, moderately high, and high vegetation coverage made up 41.91%, 38.89%, and 36.99%, respectively. In contrast, in 2015, 2020, and 2024, the proportions of low and moderately low vegetation coverage decreased to 50.89%, 48.15%, and 45.60%, whereas the proportions of moderate, moderately high, and high vegetation coverage increased to 49.11%, 51.85%, and 54.40%, respectively. These results indicate that prior to 2010, the basin was dominated by low and moderately low vegetation coverage. After the start of aircraft-based cloud seeding operations in 2010, the proportion of low and moderately low coverage areas gradually declined, while areas with moderate to high vegetation coverage expanded. A clear reversal in vegetation coverage trends was observed, beginning around 2010. Notably, between 2010 and 2024, moderately low coverage decreased significantly from 34.16 to 20.38%, whereas moderate coverage increased from 12.35 to 23.96%. This led to an overall expansion of moderate to high vegetation coverage ($FVC \geq 25\%$) from 36.99% in 2010 to 54.40% in 2024. These results strongly suggest a positive correlation between the cloud-seeding measures initiated in 2010 and the recovery of vegetation in the basin.

The spatial distribution of FVC (Figure 6) further shows that areas with high, moderately high, and moderate vegetation coverage were primarily concentrated in the southern and southwestern upstream mountainous regions and along river channels in the middle and lower reaches, while low and moderately low coverage was mainly distributed in the northern, northwestern, and southeastern areas. Across the six observation periods from 2000 to 2024, there is a clear trend of increasing vegetation coverage, with low-coverage areas shrinking over time. Overall, since the initiation of aircraft-based cloud seeding operations in 2010, vegetation coverage in the Shiyang River Basin has steadily improved, reflecting a general process of ecosystem recovery.

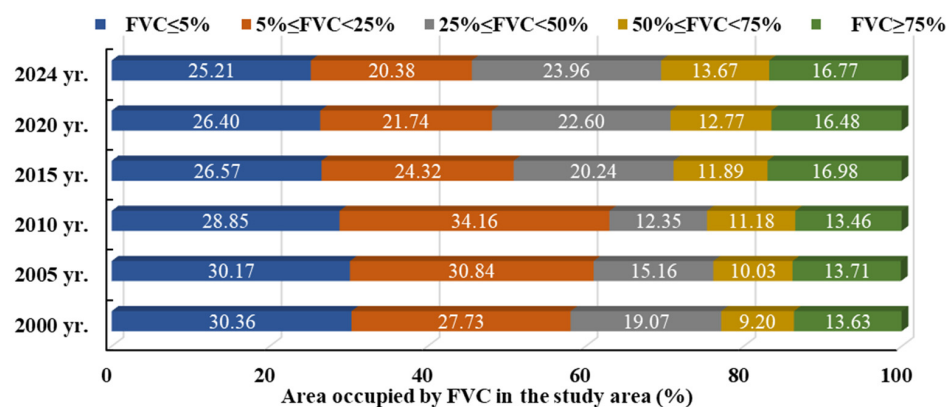


Figure 5. Proportion of area occupied by FVC in the study area.

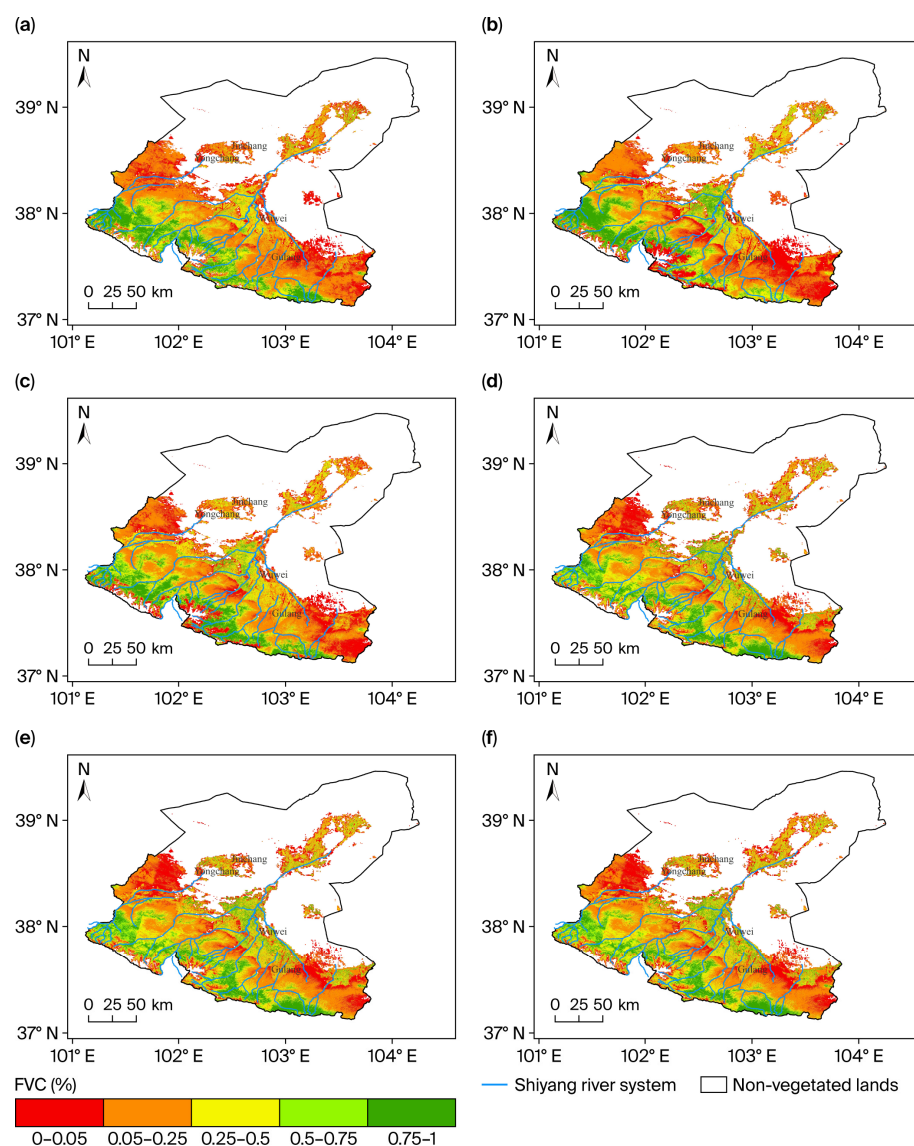


Figure 6. Spatial distribution of vegetation cover in the Shiyang River Basin during different years: (a) 2000, (b) 2005, (c) 2010, (d) 2015, (e) 2020, and (f) 2024.

4.4. FVC Trends

As shown by the statistics on FVC trends Table 4, the proportions of areas showing vegetation improvement and mild improvement increased significantly, rising from 5.46% and 8.74% during 2000–2010 to 15.91% and 20.33% during 2011–2024, with cumulative

proportions for the full 2000–2024 period reaching 9.92% and 20.83%. Conversely, the proportions of areas undergoing vegetation deterioration and mild deterioration decreased from 8.88% and 21.8% during 2000–2010 to 4.72% and 9.50% during 2011–2024. The trend of vegetation showing improvement and mild improvement has emerged as one of the most significant change patterns within the Shiyang River Basin. These results indicate that following the implementation of aircraft-based cloud seeding operations (2010–2024), vegetation conditions in the Shiyang River Basin generally stabilized, with clear improvement and effective suppression of degradation.

Table 4. Trends in FVC in the study area.

Trends	2000–2010		2011–2024		2000–2024	
	Area (km ²)	Proportion (%)	Area (km ²)	Proportion/%	Area (km ²)	Proportion (%)
Deterioration	3694.35	8.88	1963.66	4.72	1006.79	2.42
Mild Deterioration	9073.61	21.81	3952.28	9.50	2504.50	6.02
Stabilization	22,927.41	55.11	20,610.13	49.54	25,298.78	60.81
Mild Improvement	3636.10	8.74	8457.89	20.33	8665.91	20.83
Improvement	2271.54	5.46	6619.04	15.91	4127.02	9.92

Further examination of the spatial patterns of FVC in the study area (Figure 7) indicates that from 2000 to 2010, the basin displayed pronounced spatial heterogeneity. In the mid-eastern and southern mountainous regions of the upper basin, where cloud water resources are relatively abundant, FVC primarily showed improvement or slight improvement. By contrast, extensive areas of degradation persisted in the northern and central plains of the middle and lower reaches. From 2011 to 2024, vegetation restoration accelerated, with improvement areas expanding westward and toward the central basin, while deteriorated zones contracted rapidly. Vegetation restoration shows a spatial transition from local improvement to basin-wide recovery. Over the entire 2000–2024 period, improvement became the dominant spatial trend, especially in the southern, eastern, and parts of the northern basin, indicating substantial ecological recovery. In summary, during the past two decades, and particularly since 2011, with the onset of aircraft-based cloud seeding operations. The Shiyang River basin has transitioned from localized vegetation improvement to basin-wide recovery, reflecting continuous enhancement of ecological quality.

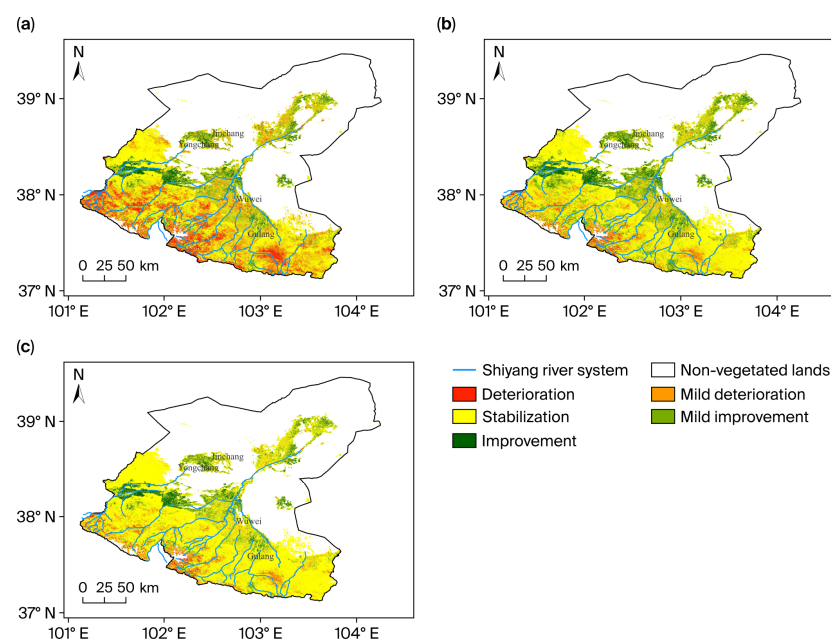


Figure 7. Trends in FVC during the growing season: (a) 2000–2010, (b) 2011–2020, and (c) 2000–2024.

The above results indicate that after the implementation of aircraft-based cloud seeding in 2010, there was a significant increase in NDVI values, indicating a restoration of vegetation. The region exhibiting low FVC reduced from 30.36% prior to the rainfall enhancement to 25.21% subsequent to it. Rainfall enhancement operations have transitioned vegetation recovery in the Shiyang River Basin from localized improvements to a comprehensive restoration across the basin, resulting in a continuous enhancement of ecological quality.

5. Discussion

The current research utilized precipitation data spanning from 1990 to 2024 and Landsat remote sensing data from 2000 to 2024. It incorporated regional historical regression, SMA, and trend analysis to investigate the effects of aircraft-based cloud seeding operations on rainfall enhancement, assess changes in vegetation coverage, and analyze FVC trends within the Shiyang River Basin. The study effectively integrates ground-based precipitation observations with high-resolution Landsat satellite imagery (2000–2024), offering a long-term and spatially detailed evaluation of rainfall enhancement and vegetation restoration. The findings indicate that ecological restoration efforts in the Shiyang River Basin have shown considerable improvement after the introduction of aircraft-based cloud seeding operations, resulting in significant increases in vegetation coverage throughout extensive regions of the basin. Localized degradation continues to be an issue, especially in the Wuwei and Minqin oases located in the middle and lower reaches. This is primarily attributed to various measures, including well closures, farmland reduction, and agricultural restructuring, which limit land reclamation efforts. Enhancing vegetation protection in the areas surrounding oasis towns and improving monitoring and management in desert regions are essential for preserving restoration achievements and avoiding additional degradation.

Extensive artificial rainfall enhancement experiments have shown that rainfall typically increases by 8–17% [30]. For example, statistical tests reported relative rainfall enhancement of 13–15% in Israel, one of the most widely recognized regions for such experiments [31]. By contrast, the Shiyang River Basin achieved a far greater enhancement of 20.8% through aircraft-based cloud seeding (Table 3). These findings highlight the exceptional effectiveness of this approach in harnessing atmospheric water resources to mitigate local water scarcity.

Meteorological records indicate that a heavy precipitation event occurred in the basin in 2002. As vegetation recovery generally exhibits a temporal lag, vegetation coverage showed an improving trend between 2000 and 2005. Long-term precipitation analysis revealed annual growth rates of 1.45% for 2000–2009 and 8.71% for 2011–2024. By examining data from 1990 to 2024, the study captures trends across more than three decades, enhancing the reliability of its findings and enabling clear differentiation between natural variability and human-induced changes. These results suggest that natural climate variability was not the main driver of FVC changes; rather, rainfall enhancement through aircraft-based cloud seeding played a decisive role in promoting ecological restoration. This finding further supports the assertion that vegetation restoration in the Shiyang River Basin is a dynamic and multifaceted process shaped by the combined effects of natural climatic variations and human-induced activities [32].

This study is notable for being among the first to provide a quantitative evaluation of aircraft-based cloud seeding in inland river basins in China, directly linking meteorological intervention to measurable ecological restoration outcomes. This research reinforces the effectiveness of aircraft-based cloud seeding as a method for harnessing atmospheric water resources in inland river basins. In the Shiyang River Basin, the operations resulted in a relative rainfall enhancement of 20.8%, which is significantly greater than levels reported internationally, and directly contributed to the improvement of the ecological environment [31]. The increase in vegetation coverage across the basin highlights the

significant impact of low-altitude operational activities on ecological restoration efforts. In certain oasis regions within the lower reaches, human activities persistently present risks of degradation. To tackle this challenge, it is essential to develop technologies for low-altitude monitoring and management, as well as to establish a low-altitude economy chain focused on “rainfall enhancement-monitoring-protection.” These efforts are crucial for solidifying restoration achievements and averting additional degradation. This study presents an innovative approach to water resource management, offering essential scientific evidence and a practical model for the integration of the low-altitude economy with ecological protection, precision agriculture, and disaster prevention and mitigation.

As the remote sensing imagery spans a long time period, slight differences in the central wavelengths of the Landsat TM/ETM+/OLI sensors and occasional poor image quality introduced some uncertainties in the retrieval results. Future studies could benefit from using harmonized satellite data or integrating multi-sensor data to improve consistency. The control area (Yongchang County) may not fully eliminate external climatic influences; a larger or multi-site control system could have strengthened the statistical robustness of rainfall comparisons. Future studies adopt multi-site control areas or spatially distributed designs to enhance the robustness of statistical comparisons. The study lacks in situ vegetation or soil validation data, relying solely on remote sensing indices, which may not capture micro-level ecological or hydrological responses. Subsequent research incorporates field surveys or high-resolution UAV data to validate micro-level ecological responses. While rainfall increases are statistically linked to cloud seeding, other concurrent ecological restoration policies (e.g., land use changes, irrigation control) may also have contributed to vegetation recovery. There is a need for more robust causal inference approaches, such as quasi-experimental designs or multi-variable modeling, in future work. The research assumes a relatively direct relationship between rainfall enhancement and vegetation improvement, but time-lagged ecosystem responses and seasonal variability are not quantitatively analyzed. Subsequent studies use time-series models (e.g., plant phenological models) to quantitatively examine these effects [29]. These factors led to relatively large variations in integration coverage and growth estimates for certain years. Addressing these limitations should be a priority for future research.

6. Conclusions

This study developed a strong analytical workflow combining regional historical regression, NDVI/FVC retrieval, and Spectral Mixture Analysis (SMA) to assess rainfall enhancement and vegetation response. We applied this framework to evaluate the effects of aircraft-based cloud seeding in the Shiyang River Basin (2010–2024), using regional historical regression and statistical tests. Additionally, it analyzed vegetation dynamics and the outcomes of ecological restoration efforts. The primary findings are outlined below:

- (1) Since the beginning of aircraft-based cloud seeding operations for rainfall enhancement (2010–2024), the total rainfall enhancement in the study area amounted to 42.9 mm, with an average relative enhancement of 20.8%, significantly surpassing findings reported in other studies. In months characterized by lower levels of precipitation, such as April and October, the impact was notably pronounced, exhibiting a relative rainfall increase exceeding 15.4%.
- (2) After the implementation of aircraft-based cloud seeding in 2010, there was a significant increase in NDVI values, indicating a restoration of vegetation. The average NDVI during the enhancement period increased by 0.119 in comparison to the pre-enhancement period.

- (3) The FVC in the Shiyang River Basin demonstrated a distinct upward trend post-2010, signifying ecosystem recovery. The region exhibiting low FVC reduced from 30.36% prior to the rainfall enhancement to 25.21% subsequent to it.
- (4) The conditions of vegetation exhibited a general trend towards stabilization, enhancement, and reduction in degradation. The proportions of areas exhibiting improvement and mild improvement saw a notable increase, escalating from 5.46–8.74% between 2000 and 2010 to 15.91–20.33% from 2011 to 2024. Cumulative proportions for the period of 2000 to 2024 reached 9.92% and 20.83%, respectively. Rainfall enhancement operations have transitioned vegetation recovery in the Shiyang River Basin from localized improvements to a comprehensive restoration across the basin, resulting in a continuous enhancement of ecological quality. The research connects scientific results to policy and management, suggesting that low-altitude economy-based cloud seeding can play a key role in water resource management, ecological stability, and climate resilience.

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