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Grey Relational Analysis of the Correlation between Various Crop Yields and Annual Precipitation in Henan Province Over the Last Decade

Rongkang Li*

College of Software, Henan Agricultural University, Xuchang, China

*Corresponding author: 2490215833@qq.com

Abstract

As a major agricultural province in China, the stable production of grain, oilseeds, and cash crops in Henan is critical to food security. In recent years, influenced by climate change, interannual precipitation fluctuations in the province have intensified, and the frequency of extreme drought and flood events has increased, exerting complex impacts on crop yields. Existing research predominantly focuses on individual crops, lacking comprehensive correlation analyses. Based on annual precipitation and major crop yield data from 2015 to 2024 in Henan Province, this study utilizes the Grey Relational Analysis (GRA) method to systematically quantify the correlation intensity between precipitation and 12 types of crops across three categories: grain, oilseed, and cash crops. Through data normalization, trend visualization, and relational grade calculation, the sensitivity differences of various crops to precipitation fluctuations were identified. This research provides theoretical and practical references for optimizing cropping structures, enhancing agricultural resilience, and ensuring food security.

Keywords

Henan Province; Precipitation; Crop Yield; Grey Relational Analysis; Cropping Structure Optimization; Food Security.

1. Introduction

Henan Province is a critical agricultural production area in China, and its diversified supply of agricultural products serves as a cornerstone of food security [1]. As the core area of grain production, Henan has established a multifaceted supply system including staple grains such as wheat and maize, as well as rice, soybeans, peanuts, rapeseed, and various cash crops [3, 7]. It is a key region for ensuring the strategy of "basic self-sufficiency in cereals and absolute security of food rations."

Agriculture is highly sensitive to climate change [2]. Influenced by global warming, interannual precipitation fluctuations in Henan have intensified over the past decade, with frequent extreme drought and flood events [4], such as the continuous rainfall in 2017 [5], periodic drought in 2019, and the extreme rainstorm in 2021. These precipitation anomalies alter the water conditions throughout the crop growth cycle, directly affecting yield and quality [4]. Existing studies have confirmed that such trends pose a severe threat to food security in major production areas [23].

However, most current research focuses on single crops [4], lacking a systematic analysis of the relationship between multiple crop categories and precipitation. Grey Relational Analysis (GRA) is particularly suitable for systems characterized by "small samples and poor information," fitting the short-sequence, multi-category scenario of this study. Therefore, this research employs GRA to quantify the correlation between annual precipitation and various crop yields in Henan from 2015 to

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2024. By identifying sensitivity differences, this study aims to provide a scientific basis for optimizing cropping structures, enhancing agricultural climate resilience, and ensuring food security.

(1) Research Objectives The objective of this study is to utilize GRA to quantify the correlation intensity between annual precipitation and 12 types of crops in Henan Province from 2015 to 2024, including grains (rice, wheat, maize, soybeans), oilseeds (peanuts, rapeseed), and cash crops (cotton, hemp, sugar crops, unprocessed tobacco, vegetables & mushrooms, and fruits). The study aims to clarify the sensitivity of crops to precipitation fluctuations and to provide scientific recommendations for regional cropping structure optimization and production regulation.

(2) Core Research Content The primary contents include: 1) Compiling a standardized dataset of precipitation and multi-category crop yields in Henan from 2015 to 2024; 2) Performing data normalization and trend visualization to analyze interannual variation characteristics; 3) Calculating the grey relational grade between precipitation and various crop yields; 4) Ranking crop sensitivity to precipitation based on the results and proposing optimized cropping structures and stress-resilience strategies adapted to regional climate characteristics.

2. Literature Review

(1) Research Progress on the Correlation Between Crop Yield and Precipitation The relationship between crop yield and precipitation is a central theme in agro-meteorological research. GRA is widely used in this field due to its ability to handle "small sample and poor information" problems. However, existing research remains insufficient regarding crop coverage and regional specificity.

International studies often focus on global or large-scale regions to analyze the overall impact of precipitation anomalies. For instance, Lobell et al. found that precipitation extremes are the primary meteorological drivers of interannual yield fluctuations in major grains, yet their study only involves a few staples, and long-term sequence analysis often fails to reflect the impact of short-term local fluctuations [8].

Domestic Chinese research is mostly concentrated on specific regions or single crops. For example, Qin et al. analyzed the impact of precipitation distribution in Southern China, but since Henan's agriculture is primarily rain-fed/dryland-based, those findings have limited reference value [9]. Within Henan, research depth is uneven: while the relationship between water and staples like wheat and maize is well-documented [10, 11], analysis of crops like cotton and soybeans is often limited to single-factor impact analysis [12, 21]. These studies lack a systematic correlation analysis and sensitivity ranking at the provincial level for multi-category crops, making it difficult to provide comprehensive decision-making evidence for cropping structure optimization.

(2) Analysis of GRA Applications in Agriculture GRA is highly suitable for "small samples and poor information" systems and is extensively applied in agro-meteorology. Research indicates it can effectively quantify the effects of meteorological factors on yields [26]. For instance, Chen et al. identified critical precipitation periods affecting spring peanut yields [14], and Zhao et al. used it to build sorghum yield prediction models [15]. Furthermore, it has been used for comprehensive evaluations of cropping patterns [16].

However, most applications focus on a single crop or a small region. Systematic analyses of multi-category crops at the provincial level are rare, especially regarding sensitivity rankings, which limits their support for regional decision-making. This underscores the necessity of this study.

(3) Analysis of Research Gaps

1) Insufficient Regional Specificity: Comprehensive studies targeting Henan's specific agro-ecological zone are lacking. Existing research often covers only sub-regions or major grains, neglecting oilseeds and cash crops [10].

2) Limited Crop Coverage: Research is highly concentrated on wheat and maize [11]. While isolated cases for cotton or soybeans exist [12, 21], they lack a unified framework for multi-category comparison.

3) Inadequate Temporal Scale Adaptation: Many valuable studies use data ending before 2017 [17, 21], failing to capture the new climate characteristics of frequent extreme precipitation in the last decade [23].

(4) Research Focus of This Paper Addressing these gaps, this study focuses on Henan Province and uses GRA to systematically quantify the correlation between annual precipitation and 12 types of crops from 2015 to 2024. The goal is to establish a sensitivity ranking to provide a scientific basis for enhancing agricultural climate resilience.

3. Technical Route and Research Methodology

(1) Technical Framework The study follows a "Data Preparation – Correlation Quantification – Conclusion Application" framework:

• Data Acquisition: Annual precipitation data (Henan Water Resources Bulletin) and yield data for 12 crops (Henan Statistical Yearbook) from 2015 to 2024 were collected.

• Data Preprocessing: This involves data cleaning (handling outliers and missing values) and Min-Max normalization to eliminate dimensional differences. Visualization via Matplotlib was used for preliminary trend analysis.

• Correlation Quantification: GRA was employed to calculate relational grades and rank the sensitivity (High, Medium, and Low).

• Conclusion Application: Based on the results and physiological characteristics of crops, optimization schemes for cropping structures were proposed to support production decision-making.

(2) Core Research Methods

• Grey Relational Analysis (GRA): This method quantifies correlation intensity by comparing the geometric similarity of sequences [18]. With precipitation as the reference sequence and yields as comparison sequences, relational grades range from 0 to 1, where higher values indicate more synchronized trends.

• Tools and Technologies: Analysis was performed using Python 3.x, specifically the Pandas (data management), NumPy (numerical computation), and Matplotlib(visualization) libraries.

4. Data Sources and Preprocessing

(1) Data Sources The data used in this study were obtained from official authoritative channels to ensure authenticity, completeness, and comparability.

• Annual Precipitation Data: Sourced from the Henan Water Resources Bulletin (2015–2024) published by the Department of Water Resources of Henan Province. It records the annual precipitation of the entire province in millimeters. These data have undergone standardized monitoring and rigorous auditing, accurately reflecting the interannual variation of precipitation over the past decade.

• Crop Yield Data: Obtained from the Henan Statistical Yearbook for the corresponding years, covering the annual total yields (unit: tons) of 12 major crops from 2015 to 2024, including grain, oilseed, and cash crops. The data statistics are standardized, and the time series is complete, allowing for precise temporal matching with precipitation data to satisfy the requirements of relational analysis.

(2) Data Preprocessing To eliminate data anomalies and unify dimensions, this study utilized Python to systematically preprocess the precipitation and crop yield data from 2015 to 2024, primarily through data cleaning and normalization.

• Outlier Handling: Outliers were detected using the Interquartile Range (IQR) method. Anomalies caused by statistical errors were replaced by the mean values of adjacent years. Only the data for 2021 (characterized by significantly high precipitation and low maize yield) was retained, as it represents objective fluctuations caused by extreme rainstorm disasters [22]; this will be specifically addressed in the subsequent analysis.

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• Missing Value Imputation: Upon inspection, all data for the ten years were complete with no missing or invalid values, thus requiring no additional imputation.

• Validation of Cleaning Results: The processed data met the requirements of completeness, authenticity, and adaptability. The standardized format allows for direct application in Grey Relational Analysis.

(3) Normalization Since precipitation is measured in millimeters and yield in tons, the significant differences in dimensions and numerical scales would cause indicators with large values to dominate the results if calculated directly. Therefore, normalization is required. This study adopts the Min-Max Normalization method to linearly transform all indicator data into the range of. This method not only eliminates dimensional influences but also fully preserves the original distribution trends and interannual fluctuation characteristics of the data, including the authentic outliers of 2021. This ensures comparability between data of different dimensions and establishes a reliable foundation for subsequent grey relational grade calculations and visual analysis. The calculation formula is as follows:

$$x_i' = \frac{x_i - \min(x)}{\max(x) - \min(x)}$$

In the formula, x_i' is the normalized value of the indicator in the i-th year; x_i is the original data in the i-th year (i=1,2,…,10, corresponding to the years 2015–2024);

$\max(x)$and $\min(x)$are the maximum and minimum values of the indicator sequence, respectively.

Table 1. Normalized Data of Precipitation and Yields of Various Grain Crops in Henan Province, 2015–2024 (Grain Category)

Year	Annual Precipitation	Rice	Wheat	Maize	Soybeans
2015	0.2923	0.6518	0	0.7673	0
2016	0.431	0.8635	0.3209	0.5497	0.0029
2017	0.499	0.2835	0.6239	0.4106	0.0702
2018	0.3774	0.6903	0.2657	0.9568	0.9487
2019	0	0.9695	0.7518	0.6433	1
2020	0.5767	1	0.7915	0.9297	0.9069
2021	1	0.1435	0.9655	0	0.5336
2022	0.1547	0.1299	1	0.7268	0.7404
2023	0.846	0.1317	0.0799	1	0.8927
2024	0.4821	0	0.9041	0.617	0.7002

Table 2. Normalized Data of Precipitation and Yields of Various Oilseed Crops in Henan Province, 2015–2024 (Oilseed Category)

Year	Annual Precipitation	Peanuts	Peanuts
2015	0.2923	0	0.6915
2016	0.431	0.106	0.1843
2017	0.499	0.3258	0.297
2018	0.3774	0.5893	0
2019	0	0.6158	0.5043
2020	0.5767	0.7284	0.6667
2021	1	0.6868	1
2022	0.1547	0.855	0.9589
2023	0.846	1	0.6504
2024	0.4821	0.996	0.8988

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Table 3. Normalized Data of Precipitation and Yields of Other Cash Crops in Henan Province, 2015–2024 (Cash Crop Category)

Year	Annual Precipitation	Cotton	Hemp	Hemp	Unprocessed Tobacco	Vegetables & Mushrooms	Fruits
2015	0.2923	1	1	1	1	0	0.2865
2016	0.431	0.6897	0.9427	0.878	0.9382	0.2064	0.732
2017	0.499	0.6108	0.7742	0.8347	0.7746	0.4321	1
2018	0.3774	0.5107	0.7312	0.749	0.6289	0.2238	0.5967
2019	0	0.3333	0.6667	0.4002	0.3616	0.3073	0.8505
2020	0.5767	0.179	0.2115	0.2752	0.1792	0.4956	0.484
2021	1	0.1182	0.1864	0.1885	0	0.4915	0
2022	0.1547	0.1117	0.1505	0.0484	0.0681	0.6755	0.2247
2023	0.846	0.0115	0.0896	0	0.021	0.8302	0.205
2024	0.4821	0	0	0.0192	0.0189	1	0.4016

5. Data Analysis and Results

5.1 Visualization of Temporal Trends by Crop Category

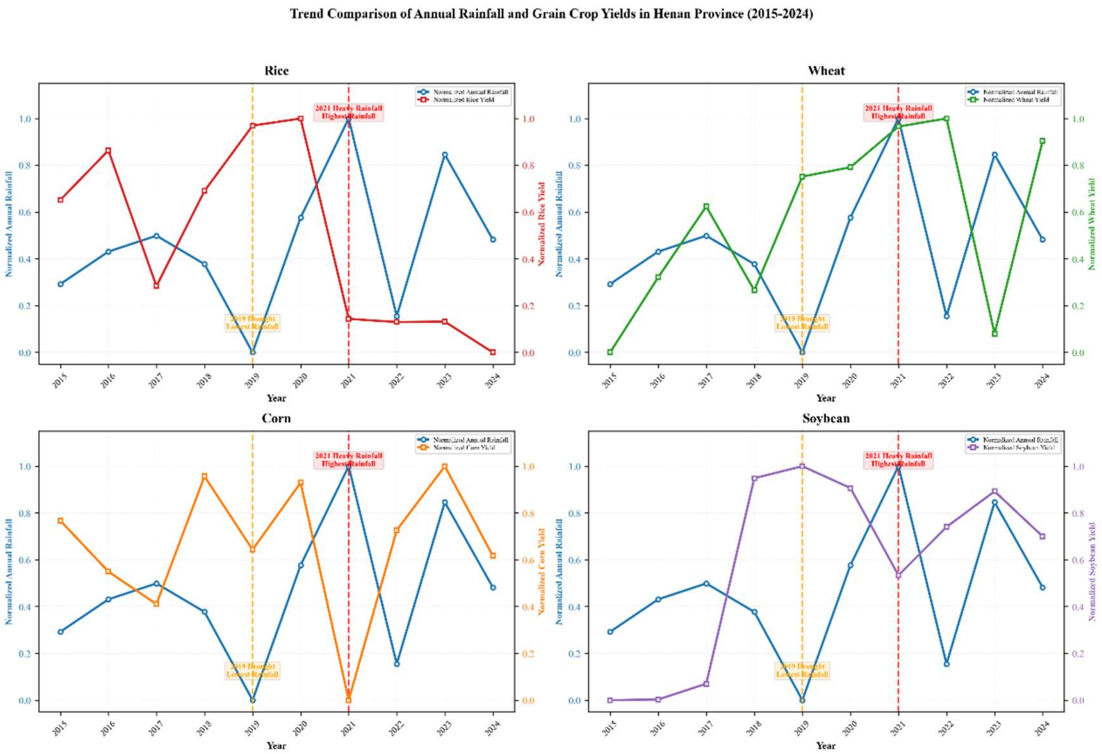

Figure 1. Comparison of Trends Between Annual Precipitation and Grain Crop Yields in Henan Province, 2015–2024

Basic Information: The figure consists of a subplot layout corresponding to rice, wheat, maize, and soybeans. The left Y-axis represents normalized annual precipitation (blue solid line with circular markers, range 0–1), and the right Y-axis represents normalized yield (various colors with solid lines and square markers, range 0–1). An orange dashed line marks the 2019 drought (labeled "2019 Drought: Minimum Precipitation"), and a red dashed line marks the 2021 rainstorm (labeled "2021 Rainstorm: Maximum Precipitation"). The X-axis covers the period from 2015 to 2024.

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• Rice: Yield exhibited a fluctuating downward trend with a weak negative correlation with precipitation. Yield fluctuated within 10% during extreme precipitation years, indicating high tolerance.

• Evidence: In 2021, when precipitation peaked (1.0), yield was 0.14; in 2019, at the precipitation minimum (0), yield was 0.9695, showing a subtle inverse relationship.

• Wheat: Yield remained stable and was virtually independent of precipitation, likely due to sufficient irrigation infrastructure. No significant yield reduction was observed during extreme weather events [11].

• Evidence: During the 2019 drought and 2021 rainstorm, normalized yield values were 0.7518 and 0.9655, respectively, showing no marked decline.

• Maize: Shows a strong negative correlation with precipitation. Yield reached its decadal low during the 2021 rainstorm but recovered during the 2019 drought, reflecting its high sensitivity to excessive moisture during the tasseling and silking stages [13].

• Evidence: Yield and precipitation are highly inversely related; yield dropped to 0 at the 2021 precipitation peak and rose to 0.6433 at the 2019 minimum.

• Soybeans: Yield followed a "rise then stabilize" pattern, showing a moderate negative correlation with precipitation. Excessive rainfall led to yield pullbacks (approx. 15% fluctuation), though field management may have mitigated the impact.

• Evidence: Yield was 0.5336 during the 2021 precipitation peak, retreating from its 2019 peak (1.0) but avoiding a total collapse.

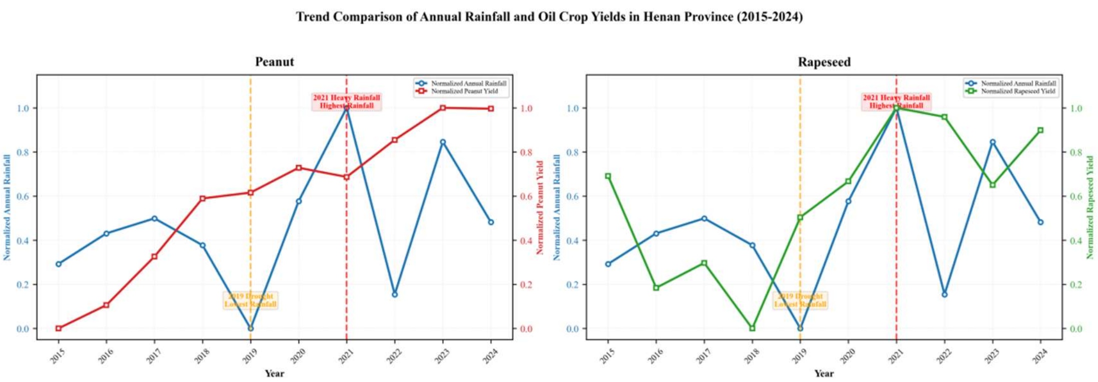

Figure 2. Comparison of Trends Between Annual Precipitation and Oilseed Crop Yields in Henan Province,2015-2024

Basic Information: This figure consists of a subplot layout corresponding to peanuts and rapeseed. The coordinate axes and extreme weather markers are consistent with Figure 5-1. Peanut yield is represented by a dark red solid line with square markers, and rapeseed yield is represented by a light red solid line with square markers.

• Peanuts: Yield exhibited continuous growth and was virtually independent of precipitation. This indicates strong tolerance to both drought and waterlogging, as extreme weather events did not interrupt the upward growth trend.

• Evidence: During the 2019 drought and 2021 rainstorm, normalized yield values were 0.6158 and 0.6868, respectively, maintaining a growth trajectory.

• Rapeseed: Yield showed a fluctuating upward trend with a weak negative correlation with precipitation. Excessive rainfall caused only minor short-term fluctuations (approx. 15%), demonstrating high adaptability [20].

• Evidence: Yield dropped to the 0–0.3 range during the relatively high rainfall years of 2017–2018 but recovered to the 0.7–0.9 range after 2021.

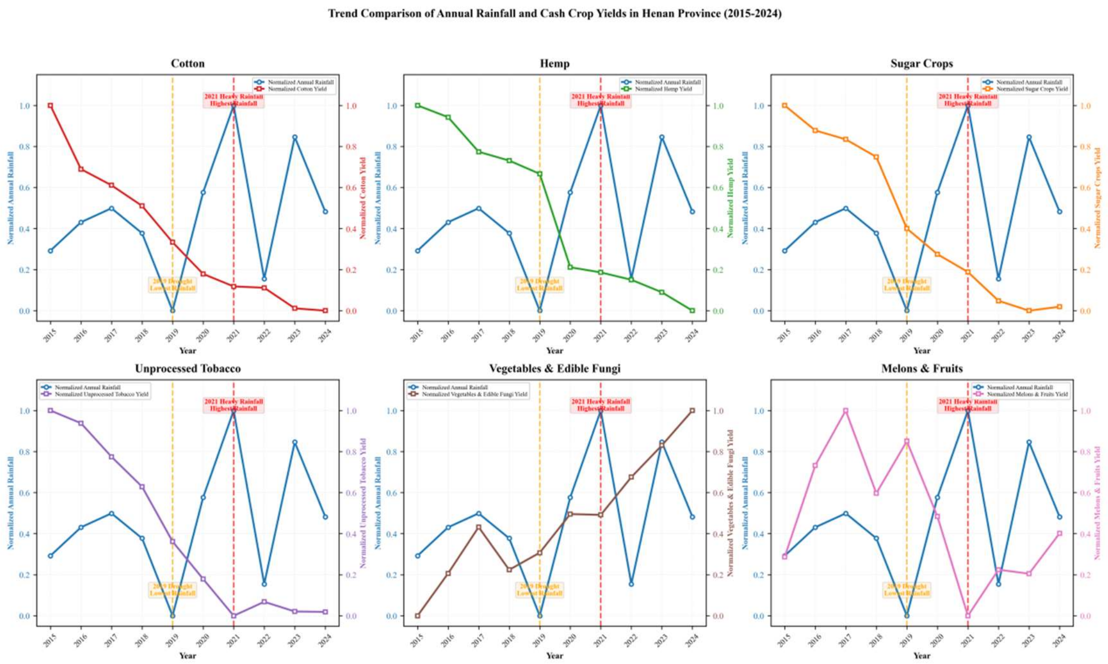

Figure 3. Comparison of Trends Between Annual Precipitation and Cash Crop Yields in Henan Province,2015-2024

Basic Information: A subplot layout corresponding to cotton, hemp, sugar crops, unprocessed tobacco, vegetables & mushrooms, and fruits. The coordinate axes and extreme weather markers are unified with the previous two figures; yields of different cash crops are represented by solid lines of various colors with square markers.

Characteristics and Evidence by Crop:

• Cotton and Hemp: Yields exhibited a continuous decline and a strong negative correlation with precipitation. Extreme rainfall events accelerated yield reduction, suggesting a potential sensitivity to waterlogging [12].

• Evidence: A steady decline occurred from 2015 to 2024; during the 2021 precipitation peak, the normalized yield values were 0.1182 and 0.1864, respectively, a significant drop from the 2015 peak (1.0).

• Sugar Crops and Unprocessed Tobacco: Yields showed a slow downward trend with a moderate negative correlation with precipitation. Rainfall primarily acted as a factor that exacerbated yield reductions.

• Evidence: There was an overall slow decline, with the magnitude of yield reduction expanding during the 2021 precipitation peak.

• Vegetables & Mushrooms and Fruits: The yield of vegetables and edible mushrooms showed nearly continuous growth and was largely independent of precipitation. Fruit yields exhibited fluctuations but showed low correlation with precipitation. Both categories rely heavily on facility agriculture, such as greenhouses and drip irrigation, demonstrating the strongest stress resilience.

• Evidence: During the 2021 rainstorm, vegetable and mushroom yields remained stable at approximately 0.49, while fruit yields briefly dropped to 0 before a rapid recovery.

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5.2 Results of Grey Relational Grade Calculation Based on the Normalized Data of Precipitation and the Yields of 12 Crop Types in Henan Province from 2015 to 2024, this Study Quantified the Correlation Intensity Using Grey Relational Analysis (GRA).

(1) Analytical Method and Procedures Grey Relational Analysis is a multi-factor statistical analysis method used to rank factors affecting system behavior. Its core principle involves judging the degree of correlation by comparing the geometric similarity of data curves; the closer the curves, the higher the relational grade [18].

The specific calculation procedures are as follows [18]:

1. Determine the Sequences:

Reference sequence

$$X_0=\{X_0(1),X_0(2),\ldots,X_0(n)\}. \tag{1}$$

Comparison sequence

$$X_i=\{X_i(k)|k=1,2,\ldots,n;\ i=1,2,\ldots,m\}. \tag{2}$$

2. Calculate Initial Values: The Min-Max normalization method is adopted, which preserves the relative relationships within the data while unifying the dimensions (units). This method also retains the authentic outliers of the 2021 precipitation event. The calculation formula is as follows:

$$x_i'=\frac{x_i-\min(x)}{\max(x)-\min(x)} \tag{3}$$

3. Calculate the Correlation Coefficient:

First, substitute into formula (4) to obtain the absolute difference between the sequences:

$$\Delta_i(k)=|X_0'(k)-X_i'(k)|; \tag{4}$$

Then, substitute into formula (5):

$$\xi_i(k)=\frac{\min_i \min_k \Delta_i(k)+\rho \max_i \max_k \Delta_i(k)}{\Delta_i(k)+\rho \max_i \max_k \Delta_i(k)}; \tag{5}$$

In the formula, ρ is the resolution coefficient, with a value range of (0， 1), and 0.5 is commonly selected.

4. Calculate the Relational Grade: Sum the correlation coefficients and calculate their average, as shown in formula (6):

$$r_i=\frac{1}{n}\sum_{k=1}^{n}\xi_i(k),\ k=1, 2,\ldots,n. \tag{6}$$

5. Ranking: Rank the results based on the magnitude of the grey relational grade. A larger value indicates a stronger correlation.

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The grey relational grades between the yields of other various crop types and the annual precipitation in Henan Province over the past decade can be derived by following the aforementioned calculation methods and procedures for each crop.

(2) Classification Standards for Sensitivity Levels To objectively evaluate the degree of crop response to fluctuations in annual precipitation, and based on empirical thresholds in agro-meteorological research combined with the characteristics of the current dataset [14, 19], the following standards have been established:

High-sensitivity crops: Relational grade $r_i \geq 0.7$, Annual precipitation is one of the dominant factors for yield fluctuations, and the trends of yield and precipitation are highly consistent.

Medium-sensitivity crops: Relational grade $0.60 \leq r_i < 0.70$. Annual precipitation has an observable impact on yield, but is not the sole dominant factor.

Low-sensitivity crops: Relational grade $r_i < 0.60$. Annual precipitation has a weak impact on yield; production is primarily regulated by non-natural precipitation factors such as irrigation and facility agriculture.

Table 4. Classification Standards for Precipitation Sensitivity Levels of Crops

Sensitivity Level	Range of Grey Relational Grade
High-sensitivity crops	$r_i \geq 0.7$
Medium-sensitivity crops	$0.60 \leq r_i < 0.70$
Low-sensitivity crops	$r_i < 0.60$

Table 5. Results of Grey Relational Grades, Rankings, and Sensitivity Levels for 12 Crop Types

Rank	Crop Category	Crop Name	Grey Relational Grade	Sensitivity Level
1	Cash Crops	Vegetables & Mushrooms	0.6894	Medium
2	Cash Crops	Fruits	0.6531	Medium
3	Oilseeds	Rapeseed	0.6501	Medium
4	Grains	Wheat	0.6411	Medium
5	Oilseeds	Peanuts	0.6187	Medium
6	Grains	Maize	0.6009	Medium
7	Cash Crops	Cotton	0.6003	Medium
8	Grains	Soybeans	0.5699	Low
9	Grains	Rice	0.5556	Low
10	Cash Crops	Unprocessed Tobacco	0.5440	Low
11	Cash Crops	Hemp	0.5425	Low
12	Cash Crops	Sugar Crops	0.5390	Low

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(1) Analysis of High-Sensitivity Crops According to the classification standards for high-sensitivity crops (), none of the 12 crops fall into this category, which is consistent with the research trends observed in the North China Plain. Studies have shown that improvements in irrigation facilities, variety updates, and optimization of field management have significantly reduced the sensitivity of crops in the North China Plain to drought [24], confirming that the agricultural climate resilience in Henan is enhancing. As a core agricultural production area, Henan has long improved its infrastructure and promoted agricultural technologies, substantially strengthening the buffering capacity of agriculture against precipitation fluctuations. Even during the extreme rainstorm of 2021, there was no violent fluctuation where crop yields were nearly synchronized with precipitation.

(2) Analysis of Medium-Sensitivity Crops There are 7 types of medium-sensitivity crops (), accounting for 58.3% of the total and covering all three major crop categories. This indicates that annual precipitation has a clear but non-decisive impact on more than half of the major agricultural crops in Henan.

• Grain Crops: Wheat (relational grade 0.6411, ranked 4th) and maize (0.6009, ranked 6th). Some studies suggest that precipitation is the primary factor affecting the irrigation water requirement of winter wheat and summer maize [11]. This study confirms a medium correlation between the two and annual precipitation, but modern irrigation has shifted natural precipitation from an "absolute dominant factor" to an "important influencing factor." Maize showed a significant yield reduction during the extreme rainstorm of 2021, which aligns with its sensitivity to moisture during the tasseling and silking stages, further confirming that a mismatch between precipitation and water requirements exacerbates yield fluctuations [13].

• Oilseed Crops: Rapeseed (relational grade 0.6501, ranked 3rd) and peanuts (0.6187, ranked 5th). Although peanuts show a medium correlation with precipitation, their yield has grown continuously, indicating that variety tolerance and planting techniques have offset some impacts of precipitation fluctuations. The higher relational grade for rapeseed may be related to the alignment of its growth cycle with the seasonal distribution of precipitation in Henan.

• Cash Crops: Vegetables & mushrooms (relational grade 0.6894, ranked 1st), fruits (0.6531, ranked 2nd), and cotton (0.6003, ranked 7th). The relational grades for vegetables, mushrooms, and fruits reflect the indirect connection between open-field cultivation or facility environments and the external climate. The correlation characteristics of cotton are consistent with related research directions [12], reflecting the observable impact of provincial-scale precipitation on its yield.

(3) Analysis of Low-Sensitivity Crops There are 5 types of low-sensitivity crops (), accounting for 41.7% of the total. Their yield stability is minimally affected by annual precipitation.

• Grain Crops: Soybeans (relational grade 0.5699, ranked 8th) and rice (0.5556, ranked 9th). Rice is mainly cultivated in the Yellow River irrigation areas and southern Henan, where irrigation conditions are superior [6], leading to a low dependence on natural precipitation. Soybeans have a lower relational grade, which is related to their short growth cycle, drought tolerance, and rotation management.

• Cash Crops: Unprocessed tobacco (relational grade 0.5440, ranked 10th), hemp (0.5425, ranked 11th), and sugar crops (0.5390, ranked 12th). These crops have small and concentrated planting areas, and their yield changes are primarily driven by socio-economic factors such as planting structure adjustments, market demand, and policy guidance [7]. The overall downward trend over the past decade shows an extremely low correlation with precipitation fluctuations.

The top two positions in relational grades are occupied by cash crops (vegetables & mushrooms, fruits), followed by an oilseed crop (rapeseed) and a staple grain (wheat); the bottom three are all cash crops (sugar crops, hemp, unprocessed tobacco). This pattern demonstrates that some cash and oilseed crops respond to annual precipitation no less than traditional staple grains, while the stability of other cash crops, as well as rice and soybeans, depends more on non-climatic factors. This provides a direct basis for the regional optimization of cropping structures.

6. Discussion of Results and Suggestions for Planting Optimization

6.1 Interpretation of the Rationality of Correlation Results

The absence of high-sensitivity crops indicates that Henan has established a production model dominated by irrigated agriculture through the construction of high-standard farmland and the promotion of agricultural technology [3]. This has effectively buffered the stress of natural precipitation, confirming the assertion that "climate change has a significant impact on crop yields but is not the sole determinant" [17].

With more than half of the crops classified as medium-sensitivity, it is evident that natural precipitation remains a crucial environmental factor in Henan's agricultural production [2]. The moisture sensitivity of maize aligns with its physiological characteristics. Although wheat shows a medium correlation with precipitation, its yield stability is ensured by a sophisticated irrigation network and agronomic management. The correlation characteristics of peanuts and rapeseed are closely related to variety adaptability and the alignment of precipitation with their growth cycles [20]. The correlation observed for vegetables, mushrooms, and fruits stems from the impact of precipitation on open-field cultivation portions. The correlation intensity of cotton reflects the observable effect of provincial-scale precipitation on its yield.

Among the low-sensitivity crops, rice yield is highly dependent on artificial irrigation. The low sensitivity of soybeans is influenced by their growth cycle characteristics and planting patterns. Meanwhile, yield changes in most cash crops, such as hemp, sugar crops, and unprocessed tobacco, are primarily driven by socio-economic factors [7]. Overall, the correlation between crops in Henan and annual precipitation is mostly medium-to-low, a characteristic that profoundly reflects the complex interaction between natural climatic factors and human management systems [25].

6.2 Targeted Suggestions for Planting Optimization

(1) Regional and Categorical Adjustments: In the rain-prone and waterlogging-susceptible regions or years of southern and southeastern Henan, the cultivation of maize and cotton should be reduced, while peanuts and vegetables should be expanded, alongside the development of integrated rice-fish farming. In the arid, low-rainfall hilly regions or years of western and northern Henan, wheat irrigation should be stabilized, drought-resistant crops like millet should be promoted, and soybean planting should be moderately encouraged.

(2) Implementation of Complementary Planting Models: In the wheat-maize rotation areas of the eastern Henan plain, pilot "wheat-maize/soybean strip compound planting" was conducted to diversify climate risks using soybeans. In cash crop areas, promote intercropping systems such as "open-field vegetables + facility vegetables" and "fruits + drought-resistant coarse grains" to balance economic benefits with risk-resistance capabilities.

(3) Supportive Precision Stress-Resilience Technologies: For medium-sensitivity crops like maize and cotton, focus on promoting waterlogging/drought-tolerant varieties and technologies such as subsoiling, ridge cultivation, and integrated water-fertilizer management. For facility vegetables and fruits, upgrade to high-standard facilities and intelligent control systems. For low-sensitivity crops undergoing reduction, enhance market alignment and policy guidance.

7. Limitations and Future Outlook

7.1 Research Limitations

This study has the following limitations:

(1) Spatial Scale Constraints: Provincial-level data fails to reflect the spatial differences among ecological sub-regions such as northern and western Henan, leading to insufficient specificity in recommendations.

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(2) Single Influencing Factor: The study only focuses on annual precipitation and does not incorporate temperature, the distribution of precipitation during growth cycles, or non-climatic factors such as varieties and policies.

(3) Insufficient Sub-categorization of Crops and Cropping Systems: Differences in varieties and the impact of different cropping systems (e.g., monoculture vs. intercropping) on moisture response were not considered.

(4) Low Temporal Scale Matching: The annual precipitation indicator is not precisely matched with the critical water-demand periods of crops, which may mask the extreme impacts of moisture stress during those key stages.

7.2 Future Outlook

Subsequent research could focus on:

(1) Conducting correlation analysis at the municipal, county, or grid level to map the spatial distribution of sensitivity.

(2) Constructing comprehensive models that integrate meteorological, soil, management, and socio-economic factors to identify the role of precipitation more comprehensively.

(3) Focusing on the quantitative relationship between precipitation indicators during critical growth cycles and yield to support precision field management.

(4) Integrating big data with crop models to develop yield prediction and planting optimization decision-support systems, thereby enhancing agricultural climate adaptability.

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