

Spatiotemporal Variation Characteristics of Precipitation Concentration Degree and Concentration Period in the Loess Plateau Region over the Past 60 Years: Postprint

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Abstract

Under the background of global climate warming, elucidating the spatiotemporal variation patterns of precipitation concentration degree (PCD) and precipitation concentration period (PCP) in the Loess Plateau region is of great significance for soil and water conservation and water resource utilization in this area. Based on daily precipitation observation data from 55 meteorological stations in the Loess Plateau region from 1960 to 2019, and using methods such as trend analysis, spatial interpolation, and correlation analysis, this study analyzed the spatiotemporal variation characteristics of PCD and PCP in the Loess Plateau during the past 60 years and before and after the Grain-for-Green (GFG) project. The results indicate: (1) From 1960 to 2019, the mean annual precipitation in the Loess Plateau exhibited a decreasing trend, the mean annual PCD gradually weakened, and the PCP gradually advanced. (2) In the Loess Plateau region, mean annual precipitation and PCD decreased from southeast to northwest, while PCP gradually decreased from east to west, albeit with small differences. The trend of PCD change exhibited an alternating distribution of “decrease-increase-decrease” from northeast to southwest, while PCP showed a pattern of delay in the east and advancement in the west. (3) After the implementation of the Grain-for-Green project, the mean annual precipitation in the Loess Plateau increased, PCD weakened, and PCP was delayed. Precipitation displayed an alternating distribution of “below normal-above normal” from east to west, with the change trend being predominantly above normal; PCD showed a distribution pattern of “low-high-low” from northeast to southwest, with the change trend being predominantly low; PCP was predominantly high (i.e., delayed), with the magnitude of being high showing a pattern of more in the south and less in the north, more in the east and less in the west, and its trend change was also predominantly above normal. (4) From 1960 to 2019,

PCD, PCP, and annual precipitation in the Loess Plateau region were mainly positively correlated.

Full Text

Temporal and Spatial Variation Characteristics of Precipitation Concentration Degree and Precipitation Concentration Period on the Loess Plateau from 1960 to 2019

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Abstract

Against the backdrop of global climate warming, clarifying the spatiotemporal variation patterns of precipitation concentration degree (PCD) and precipitation concentration period (PCP) on the Loess Plateau is crucial for soil and water conservation and water resource utilization in this region. Based on daily precipitation observations from 55 meteorological stations across the Loess Plateau from 1960 to 2019, this study analyzes the temporal and spatial variation characteristics of PCD and PCP over the past 60 years, as well as before and after the implementation of the “returning farmland to forest (grassland)” project, using trend analysis, spatial interpolation, and correlation analysis methods. The results indicate: (1) From 1960 to 2019, the average annual precipitation on the Loess Plateau showed a decreasing trend, while the annual average PCD gradually weakened and the PCP progressively advanced. (2) Both annual precipitation and PCD decreased from southeast to northwest, whereas PCP gradually decreased from east to west, though the differences were relatively small. The PCD trend exhibited an alternating distribution pattern of “decline-rise-decline” from northeast to southwest, while PCP demonstrated a pattern of delay in the east and advancement in the west. (3) Following the “returning farmland to forest (grassland)” project, the average annual precipitation on the Loess Plateau increased, PCD weakened, and PCP was postponed. Precipitation showed an alternating “below average-above average” distribution pattern from east to west, with the trend predominantly above average. PCD displayed a “low-high-low” distribution pattern from northeast to southwest, with the trend primarily low. PCP was predominantly high, with the magnitude of increase showing a pattern of more in the south than north and more in the east than west, and its trend change was also mainly above average. (4) During 1960-2019, PCD, PCP, and annual precipitation on the Loess Plateau were primarily positively correlated.

Keywords: precipitation concentration degree (PCD); precipitation concentra-

tion period (PCP); returning farmland to forest (grassland) project; ecological zoning; Loess Plateau

1. Introduction

Global climate change has made the analysis of precipitation concentration characteristics and their causes increasingly important [1]. Precipitation concentration reflects the comprehensive interplay of precipitation amount, duration, and process [2]. The IPCC' s Sixth Assessment Report indicates that human activities have caused approximately 1.07°C of global mean surface temperature increase compared to pre-industrial levels [3]. There is unequivocal evidence that human influence has intensified atmospheric, oceanic, and terrestrial warming, directly leading to sharp increases in the frequency and intensity of typical extreme climate events such as extreme heat, persistent heavy precipitation, and extreme drought [4]. Global water resources may follow a “dry gets drier, wet gets wetter” paradigm [5], posing severe challenges to sustainable socio-economic development [6]. For instance, from 08:00 on July 19 to 22:00 on July 20, 2021 (Beijing Time), Zhengzhou experienced historically rare extreme rainfall under the influence of the easterly jet on the periphery of the Huang-Huai low vortex, with cumulative precipitation reaching 817.3 mm and a maximum value of 645.6 mm between 04:00 and 21:00 on July 20. This excessive precipitation concentration caused severe landslides, debris flows, urban waterlogging, and casualties [7]. Therefore, analyzing precipitation concentration characteristics is essential.

Scholars commonly use indices such as the precipitation concentration degree (PCD) and precipitation concentration period (PCP) defined by Zhang et al. [8], the precipitation concentration index (PCI) defined by Martin-Vide [9], the precipitation concentration index (PCI) defined by Oliver [10], and the precipitation concentration degree (Q) defined by Wang et al. [11] to analyze precipitation concentration characteristics. Among these, PCD and PCP can simultaneously quantify both the degree and timing of precipitation concentration [12] and have been widely applied in related research [13-15].

The Loess Plateau is the world' s largest loess accumulation area, characterized by highly fragile ecological environments and severe soil erosion, which are closely related to its special soil structure, ecological conditions, and concentrated precipitation with frequent heavy rains [16]. Chinese scholars have conducted extensive research on the spatiotemporal variation characteristics of precipitation [17-19], extreme precipitation [20-22], and precipitation days and intensity at different grades [23-25] on the Loess Plateau. However, reports on intra-annual precipitation distribution characteristics in this region remain relatively scarce. Liu et al. [26] used daily precipitation data from 1959-2008 to study the temporal and spatial variation characteristics and trends of precipitation concentration degree and period on the Loess Plateau. Since the implementation of the “returning farmland to forest (grassland)” project in

1999, vegetation cover on the Loess Plateau has significantly improved, and precipitation has increased [27], effectively alleviating soil erosion in the region. However, what impact has this project had on precipitation concentration degree and period on the Loess Plateau? This study calculates PCD and PCP for the Loess Plateau using daily precipitation data from 1960-2019 and analyzes the spatiotemporal variation characteristics of uneven precipitation distribution in the region using trend analysis, spatial interpolation, and correlation analysis methods. The findings provide a scientific basis for comprehensively understanding intra-annual precipitation variation patterns and rationally utilizing water resources on the Loess Plateau.

2. Data and Methods

2.1 Data Sources Daily precipitation data from 1960-2019 were obtained from the China Meteorological Data Network (<http://data.cma.cn/>). Following the principles of data integrity (annual missing data < 5%), long observation periods, and no station relocation, 55 representative meteorological stations were ultimately selected (Fig. 1). Station precipitation data quality was checked using the RHtest method [28].

Based on previous research results, the Loess Plateau was divided into four ecological zones: highland gully region (I), hilly-gully region (II), sandy agricultural irrigation region (III), and rocky valley region (IV). The data were sourced from the National Earth System Science Data Center—Loess Plateau Subcenter (<http://loess.geodata.cn>).

2.2 Research Methods The calculation of PCD and PCP follows the principle described in reference [8], treating daily precipitation amounts as vector lengths and corresponding dates as vector directions to characterize the intra-annual non-uniform distribution of precipitation at individual stations. The formulas are:

$$PCD_i = \frac{\sum_{j=1}^n r_{ij} \times \sin \theta_j}{\sum_{j=1}^n r_{ij} \times \cos \theta_j}$$

$$PCP_i = \arctan \left(\frac{\sum_{j=1}^n r_{ij} \times \sin \theta_j}{\sum_{j=1}^n r_{ij} \times \cos \theta_j} \right)$$

where:

- j is the day number in the year ($j = 1, 2, 3, \dots, 365$ or 366)
- i is the year ($i = 1960, 1961, 1962, \dots, 2019$)
- r_{ij} is the daily precipitation amount
- R_i is the annual precipitation total for year i
- $\theta_j = 360^\circ \times (j-1)/365$ (or 366 for leap years) is the azimuth angle corresponding to day j

According to formula (1), PCD reflects the concentration degree of annual precipitation within the year, with values ranging between 0 and 1. When PCD approaches 0, precipitation distribution is more uniform, indicating near-equal distribution throughout the year. When PCD approaches 1, precipitation becomes more concentrated on a particular day, representing the day with maximum precipitation. PCP reflects the timing of maximum annual precipitation and can be converted to the day number within the year [12].

Long-term trends in annual precipitation, PCD, and PCP at each station on the Loess Plateau were calculated using linear regression [29], with significance tested using F-tests and classified as extremely significant ($P < 0.01$), significant ($P < 0.05$), or non-significant ($P > 0.05$). Spatial interpolation was performed using the inverse distance weighting method in ArcGIS software [30]. Pearson correlation coefficients between PCD, PCP, and precipitation were calculated using SPSS 26.0, with significance classified as extremely significant ($\alpha < 0.01$), significant ($\alpha < 0.05$), or non-significant ($\alpha > 0.05$).

The periods 1960-1999 (T1) and 2000-2019 (T2) were defined as before and after the “returning farmland to forest (grassland)” project, respectively. The averages and trends of precipitation, PCD, and PCP were calculated for each period to compare and analyze the differences before and after the project.

3. Results

3.1 Basic Climatic and Environmental Characteristics of the Loess Plateau From 1960-2019, the average precipitation on the Loess Plateau showed a decreasing trend at a rate of $-0.148 \text{ mm} \cdot \text{a}^{-1}$, with an average value of 422.76 mm, slightly lower than the decreasing rate calculated from gridded precipitation data [31]. Interdecadal precipitation showed a pattern of “decrease-increase-decrease” with a significant turning point in the 1990s. Due to different geographical locations and moisture sources, precipitation variation characteristics differed among ecological zones.

In terms of average annual precipitation over the past 60 years, the ecological zones ranked from high to low as: rocky valley region (529.46 mm), hilly-gully region (456.86 mm), highland gully region (417.84 mm), and sandy agricultural irrigation region (302.93 mm). Regarding trends, except for the rocky valley region where annual precipitation showed a decreasing trend, all other ecological zones showed increasing trends, with the hilly-gully region showing the most significant increase (21.67 mm). During the 2000s, precipitation in the Loess Plateau and all ecological zones except the rocky valley region increased, while during the 2010s, all zones showed increasing trends, with the hilly-gully region showing the most obvious increase (Table 1). Overall, the interdecadal precipitation in each ecological zone exhibited a “first decrease then increase” pattern, with the lowest values occurring in the 1990s for the highland gully and sandy agricultural irrigation regions, and in the 1980s for the hilly-gully and rocky valley regions. The highest values occurred in the 1960s for the rocky valley

region and in the 1990s for other zones.

Spatially, the average annual precipitation on the Loess Plateau showed a decreasing pattern from southeast to northwest (Fig. 2a). Specifically, precipitation exceeded 500 mm in the central-southern Fenwei Plain of the rocky valley region, southeastern highland gully region, and southern hilly-gully region. Precipitation ranged 400-500 mm in the southeastern area from Hohhot to Tongren, 300-400 mm in the narrow belt from northwestern highland gully region to central-eastern sandy agricultural irrigation region, and below 200 mm in the central-western sandy agricultural irrigation region and northern highland gully region. The spatial distribution of precipitation variation coefficient showed a south-low and north-high pattern, approximating zonal distribution (Fig. 2b). The lowest variation coefficients occurred in the western north-south sides of the highland gully region, indicating the most stable precipitation, while the highest coefficients (above 0.4) occurred in the northwestern sandy agricultural irrigation region, showing the most unstable precipitation. Overall, precipitation in southern Loess Plateau was abundant and stable, while in the northwest it was scarce and unstable.

After the “returning farmland to forest (grassland)” project, precipitation change trends on the Loess Plateau were predominantly above average, with the highest increase in the Hengshan-Suide area of the hilly-gully region exceeding $12 \text{ mm} \cdot \text{a}^{-1}$. Additionally, a secondary above-average center formed in the central-southern highland gully region, with increase rates between $8\text{-}12 \text{ mm} \cdot \text{a}^{-1}$. The spatial distribution of precipitation showed an alternating “below average-above average” pattern from east to west (Fig. 2c), with the most significant decreases in the central and southeastern rocky valley region, related to its location at the interface between the Asian monsoon and mid-latitude westerlies [32].

3.2 Temporal and Spatial Variation of PCD and PCP

3.2.1 Temporal Variation The average annual PCD on the Loess Plateau fluctuated between 0.401-0.761, with a multi-year average of 0.692, significantly higher than the national average (0.15-0.25) [33], indicating relatively concentrated intra-annual precipitation distribution (Fig. 3). The interannual variation showed an inverted “V” shape with a significant turning point in the 1990s. Overall, PCD in southern Loess Plateau decreased insignificantly at a rate of $-0.044 \cdot (10\text{a})^{-1}$ ($P > 0.05$), consistent with the national trend [34], suggesting gradually weakening precipitation concentration and more uniform daily precipitation distribution, though the magnitude of change was limited.

From the perspective of ecological zones (Table 2), PCD ranked from high to low as: sandy agricultural irrigation region, hilly-gully region, highland gully region, and rocky valley region, with values of 0.753, 0.692, 0.692, and 0.485, respectively. The interannual variation characteristics of PCD in the highland gully, hilly-gully, and sandy agricultural irrigation regions were consistent with the entire Loess Plateau, showing inverted “V” curves with slightly different

turning decades. The rocky valley region showed an inverted “V” curve as well. All ecological zones exhibited decreasing PCD trends, with the hilly-gully region showing the largest decrease $[-0.168 \cdot (10a)^{-1}]$, followed by the sandy agricultural irrigation region $[-0.043 \cdot (10a)^{-1}]$ and rocky valley region $[-0.043 \cdot (10a)^{-1}]$, with the highland gully region showing the smallest decrease $[-0.007 \cdot (10a)^{-1}]$.

Before 1999, the average annual PCD on the Loess Plateau was 0.701 with large fluctuations, while after 1999 it became 0.665 with smaller fluctuations, indicating weakened PCD after the project. The PCD trend shifted from an increasing rate $[0.044 \cdot (10a)^{-1}]$ before the project to a decreasing rate $[-0.043 \cdot (10a)^{-1}]$ after the project.

The average annual PCP on the Loess Plateau fluctuated between 203.72-209.17 days (late July), with a multi-year average of 207.22 days, indicating that the maximum daily precipitation occurred around late July (Fig. 3). The interannual variation showed a “V” curve with a significant turning point in the 1990s. Overall, PCP decreased at a rate of $-0.1114 \text{ d} \cdot (10a)^{-1}$ ($P > 0.05$), suggesting the date of maximum precipitation gradually advanced. The PCP ranking from early to late was: highland gully region (206.24 d), rocky valley region (207.51 d), hilly-gully region (207.81 d), and sandy agricultural irrigation region (207.52 d). The interannual variation characteristics of PCP in the highland gully and rocky valley regions were consistent with the entire plateau, showing “V” curves with turning points in the 1990s, while the hilly-gully and sandy agricultural irrigation regions showed inverted “V” curves.

Before 1999, the average annual PCP was 206.58 days with large fluctuations, while after 1999 it was 208.5 days with smaller fluctuations. Both stages showed decreasing trends, but the decreasing rate was lower after the project than before, indicating a postponement of PCP after the project. Comparing before and after the project, all zones except the rocky valley region showed consistent decreasing trends, with the magnitude ranking as: sandy agricultural irrigation region $[-1.497 \text{ d} \cdot (10a)^{-1}] >$ highland gully region $[-0.753 \text{ d} \cdot (10a)^{-1}] >$ hilly-gully region $[-0.792 \text{ d} \cdot (10a)^{-1}]$.

3.2.2 Spatial Variation The average annual PCD on the Loess Plateau showed a decreasing pattern from southeast to northwest, with obvious zonal characteristics (Fig. 4a), indicating that precipitation became more uniform from northwest to southeast as precipitation amount increased. This is consistent with Liu et al. [26]. The average annual PCP showed little overall difference, decreasing gradually from east to west (Fig. 4b). Specifically, PCP was latest in the area from southeastern hilly-gully region to eastern sandy agricultural irrigation region, and earliest in the Menyuan-Lintao area of western highland gully region.

Regarding change trends (Fig. 4c), PCD on the Loess Plateau showed an alternating “decline-rise-decline” pattern from northeast to southwest. Among 55 meteorological stations, 18 showed increasing PCD trends, most notably at Wu-

gong station in southwestern highland gully region [$0.590 \cdot (10a)^{-1}$], while the most significant decrease occurred at Youyu station in northeastern hilly-gully region [$-0.690 \cdot (10a)^{-1}$].

For PCP (Fig. 4d), the Loess Plateau showed an overall pattern of delay in the east and advancement in the west. Thirty-seven stations showed delaying trends, most notably at Wuqi station in western hilly-gully region [$3.825 \text{ d} \cdot (10a)^{-1}$], while the most significant advancement occurred at Huajialing station in central highland gully region [$-0.690 \text{ d} \cdot (10a)^{-1}$]. Areas with above-average PCP were concentrated at the boundaries of four ecological zones and southwestern sandy agricultural irrigation region, particularly Zhongwei in Ningxia and Suide in Shaanxi, while below-average areas only occurred at Huajialing station in eastern Gansu.

After the project, areas with above-average PCD trends were concentrated in central-eastern hilly-gully region and central rocky valley region, with maximum increase exceeding $0.044 \cdot (10a)^{-1}$ (Fig. 5c). Areas with below-average trends were distributed in highland gully region, sandy agricultural irrigation region, and southern and northern rocky valley region, with more than 5 stations showing decreases exceeding $-0.043 \cdot (10a)^{-1}$. The average annual PCD showed an alternating “low-high-low” pattern from northeast to southwest (Fig. 5a). Above-average PCD areas were concentrated in eastern highland gully region, western sandy agricultural irrigation region, and southern rocky valley region, with Wugong station in Shaanxi showing the most significant increase (4.02 d). The most significant below-average area was in northeastern Loess Plateau with decreases exceeding -2.15 d.

The average annual PCP was predominantly above average, showing a pattern of more in the south than north and more in the east than west (Fig. 5b). The change trend was mainly above average, with a pattern of less in the southeast and more in the northwest. After the project, PCD and PCP showed inconsistent spatial combination characteristics: central and eastern regions tended toward more uniform precipitation with delayed maximum precipitation days, while western regions tended toward more concentrated precipitation with earlier maximum precipitation days.

3.3 Correlation Analysis Between PCD, PCP, and Annual Precipitation As shown in Fig. 6a, except for Guide meteorological station in southwestern Loess Plateau, PCD at all other stations was positively correlated with annual precipitation, with correlation coefficients ranging from 0.046 to 0.504. This confirms that greater annual precipitation on the Loess Plateau corresponds to more concentrated intra-annual precipitation. The correlation coefficients exceeded 0.33 in most northeastern areas (extremely significant) and reached 0.25-0.33 in central areas (significant). Stations passing significance tests accounted for 63.63% of the region.

The correlation between PCP and annual precipitation was primarily positive

but relatively weak (Fig. 6b). Notably, PCP and annual precipitation showed negative correlation along the Yellow River in western Loess Plateau, most obviously at Yinchuan station with a correlation coefficient of -0.275. Overall, annual precipitation on the Loess Plateau showed good positive correlation with PCD but poor correlation with PCP, consistent with Liu et al. [26] and also observed in the Luanhe River Basin [35].

4. Discussion

The Loess Plateau, located in a continental monsoon climate zone, has a fragile ecological environment and is highly sensitive to climate change. Since the 1960s, the average temperature has increased significantly, exceeding the national warming magnitude, with a slowdown in warming rate occurring around 1998 [36]. Extreme temperature indices have increased [37], and surface temperature has risen faster than air temperature [38]. This study found that average annual precipitation on the Loess Plateau decreased from 1960-2019, consistent with previous research [17, 31, 39]. Additionally, studies show that pan evaporation on the Loess Plateau has decreased [40].

During the study period, the average annual PCD on the Loess Plateau was relatively large but showed a slight weakening trend, with intra-annual precipitation concentrated in July. PCP advanced, and both extreme precipitation amount and days increased [41], leading to increased flood risk. For example, in July 2021, an extreme rainstorm in the Wuding River basin of northern Shaanxi caused severe soil erosion and destroyed water conservancy facilities [42]. Since large-scale implementation of the “returning farmland to forest (grassland)” project in 1999, vegetation cover on the Loess Plateau has increased significantly [43], enhancing vegetation transpiration [44] and reducing terrestrial water storage [45]. Before the project, the Loess Plateau experienced decreasing precipitation, increasing PCD, and advancing PCP. After the project, this shifted to increasing precipitation, decreasing PCD, and advancing PCP, indicating that vegetation restoration not only increases local precipitation [46] but also affects intra-annual precipitation distribution. However, the direct mechanism of how vegetation restoration affects PCD and PCP requires further investigation.

For the arid and semi-arid Loess Plateau, precipitation is the most important water source for vegetation restoration due to deep groundwater and limited surface water [47]. The increase in precipitation after vegetation restoration has important theoretical and practical significance for ecological protection and high-quality development. Further analysis shows that correlation coefficients between PCD, PCP, and annual precipitation are primarily positive, indicating that greater annual precipitation corresponds to more concentrated precipitation within the year and larger daily maximum precipitation, increasing the likelihood of floods and extreme precipitation. Additionally, due to different geographical locations and moisture sources, the spatial patterns of intra-annual precipitation distribution are inconsistent, with precipitation becoming more uniform from northwest to southeast, and PCP decreasing from east to west.

The PCD variation range of 0.401-0.761 on the Loess Plateau differs from other regions due to different study periods and station data, being larger than the 1960-2013 range (0.53-0.75) [22], the Luanhe River Basin [35], but lower than the Huaihe River Basin [48] and similar to the national average [34]. The decreasing PCD trend is consistent with the Luanhe River Basin [35] but contrary to the increasing trend in the Huaihe River Basin [48]. The average annual PCP on the Loess Plateau is slightly later than the national average [34] and the Luanhe River Basin [35], but shows a similar advancing trend. Comparison reveals that the ranking of precipitation, PCD, and PCP among the four ecological zones is inconsistent, suggesting that PCD and PCP are influenced not only by precipitation but also by topography, sunspots, and atmospheric circulation [49]. Correlation analysis between PCD, PCP, and elevation at 55 meteorological stations (Fig. 7) shows correlation coefficients of 0.504 and -0.690, respectively, both passing the extremely significant test level ($\alpha < 0.01$), indicating that higher elevation areas on the Loess Plateau have larger PCD (more concentrated precipitation) and earlier PCP. However, studies on the Jialing River Basin [50] and Pearl River Basin [51] found negative correlation between topography and PCD, warranting further investigation.

Due to limitations in precipitation data and without considering topographic effects on spatial interpolation, this study provides a preliminary analysis of the spatiotemporal variation patterns of PCD and PCP and their relationships with precipitation and topography. Precipitation distribution is influenced by multiple factors, including human activities, making PCD and PCP increasingly complex. The degree of influence of human activities, precipitation itself, atmospheric circulation, and other natural geographical factors on the spatial patterns and trend changes of PCD and PCP on the Loess Plateau, as well as their underlying mechanisms, require further exploration.

5. Conclusions

Based on daily precipitation data from 55 meteorological stations on the Loess Plateau from 1960-2019, this study calculated PCD and PCP at each station and analyzed the spatiotemporal variation characteristics of uneven precipitation distribution using climatological statistical methods. The main conclusions are:

- 1) **Temporal distribution:** The average annual precipitation on the Loess Plateau was 422.76 mm, decreasing at a rate of $-0.148 \text{ mm} \cdot \text{a}^{-1}$. The multi-year average PCD was 0.692, showing a non-significant decreasing trend ($P > 0.05$) at a rate of $-0.044 \cdot (10\text{a})^{-1}$. PCP fluctuated mainly between 203.72-216 days (late July), decreasing at a rate of $-0.1114 \text{ d} \cdot (10\text{a})^{-1}$ ($P > 0.05$). Precipitation in each ecological zone ranked as: rocky valley region > hilly-gully region > highland gully region > sandy agricultural irrigation region. PCD ranked as: sandy agricultural irrigation region > hilly-gully region > highland gully region > rocky valley region. PCP ranked as: sandy agricultural irrigation region > hilly-gully region > rocky valley region > highland gully region.

- 2) **Spatial distribution:** Average annual precipitation showed a decreasing pattern from southeast to northwest. Average annual PCD decreased from southeast to northwest, with precipitation becoming more uniform from northwest to southeast. Average annual PCP showed little overall difference, gradually decreasing from east to west. The PCD trend showed an alternating “decline-rise-decline” pattern from northeast to southwest, while PCP overall showed a pattern of delay in the east and advancement in the west.
- 3) **Changes after returning farmland to forest (grassland):** After the project, average annual precipitation on the Loess Plateau increased, PCD weakened, and PCP was postponed. Precipitation showed an alternating “below average-above average” distribution from east to west, with predominantly above-average trends showing a “low-high-low” pattern from southeast to northwest. PCD showed a “low-high-low” distribution from northeast to southwest, with predominantly low trends showing a pattern of high in the east and low in the west. PCP was predominantly high, with the magnitude of increase showing a pattern of more in the south than north and more in the east than west, and its trend change was mainly above average, showing a pattern of less in the southeast and more in the northwest.
- 4) **Correlation analysis:** During 1960-2019, PCD, PCP, and annual precipitation on the Loess Plateau were primarily positively correlated, with 63.63% of meteorological stations passing significance tests and 7.27% being extremely significant.

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