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Vegetation greening and climate change respectively regulates the long-term trend and interannual variability in evapotranspiration over the Loess Plateau since the 21st century

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Since the 21st century, large-scale afforestation projects on the Loess Plateau have resulted in significant vegetation greening, contributing to ecosystem restoration and enhanced soil conservation. However, these efforts have also led to soil aridification, declining groundwater levels, and reduced terrestrial water storage. These negative consequences are primarily attributed to increases in evapotranspiration (ET), which has augmented water consumption. Despite these findings, the underlying mechanisms driving ET variations remain contentious due to the complex interplay of multiple factors. In this study, we employed a logical attribution method, which attributes vegetation changes predominantly to anthropogenic activities (e.g., reforestation or land-use changes), while directly linking changes in climatic factors (e.g., temperature and precipitation) to climate change. We separately examined the contributions of long-term trends and interannual variability in ET to reveal distinct driving forces. Between 2000 and 2022, approximately 80% of areas showing significant changes in ET and its components were directly influenced by vegetation greening, particularly in the central part of the Loess Plateau, where restoration efforts were most prominent. In contrast, only around 20% of these changes were attributable to climate change and other factors. After removing long-term trends, interannual variations in ET were found to be more closely associated with climatic factors (temperature and precipitation), especially in arid and semi-arid regions. This indicates that climate is the dominant factor driving interannual variations in ET across the Loess Plateau. Our findings contribute to a deeper understanding of the water cycle dynamics in the context of large-scale vegetation restoration on the Loess Plateau. These insights provide a scientific foundation for policymakers to evaluate the environmental impacts and potential water-related risks associated with ecological restoration projects.

KEYWORDS

evapotranspiration, vegetation greening, climatic factors, Loess Plateau, long term trends, interannual variability

1 Introduction

The Loess Plateau is located in the transitional zone between semi-humid and arid climates in China, where the ecosystem has been highly sensitive to climate change and human disturbances (Fu, 1989; Fu et al., 2017; Jiang et al., 2021). Historically, this region was covered by grasslands and forests; however, intense human activities such as deforestation (Zheng et al., 2005) and land reclamation (Guan et al., 2020), combined with climate change, transformed it into one of the most severely eroded regions in the world, which led to a deteriorated ecological environment and significant conflicts between humans and the land (Wu et al., 2019). In recent years, with the implementation of a series of ecological restoration projects (Fu et al., 2017; Li et al., 2019), particularly following the initiation of the Grain to Green Program (GTGP) in 1999, massive greening of vegetation has become the most notable environmental change in the region since the 21st century (Liu et al., 2008; Lü et al., 2012). Vegetation cover increased by 25% between 2000 and 2010 (Feng et al., 2016), and approximately 16,000 km² of sloping farmland has been converted into artificial grasslands and forests (Nazarbakhsh et al., 2020). However, such large-scale vegetation restoration has also significantly altered regional energy balance and water cycle processes (Deng et al., 2019), thereby triggering a series of environmental and ecological effects, including some negative impacts. For instance, the newly planted vegetation may have consumed additional water from the soil, leading to soil aridification (Du et al., 2007; Deng et al., 2016; Zhang et al., 2018; Ye et al., 2019), decreased groundwater levels (Han et al., 2020), and ultimately, terrestrial water shortages (Yang et al., 2014; Deng et al., 2019). These issues are closely related to the substantial increases in evapotranspiration (ET) since the implementation of ecological restoration projects.

In the Loess Plateau, which is characterized by a semi-arid to semi-humid climate, a substantial portion of precipitation either evaporates or transpires back into the atmosphere. Consequently, understanding evapotranspiration (ET) is crucial for unraveling the regional water cycle and addressing challenges related to water resource security, particularly within the broader context of ecological restoration and greening initiatives (Reddy, 1996; Williams et al., 2004; Bai et al., 2020). Previous studies have generally identified an increasing trend in ET across the Loess Plateau (Feng et al., 2012; Wang et al., 2020; Jiao et al., 2021; Zhang et al., 2021). However, the driving factors behind this trend—such as vegetation dynamics (Bai et al., 2019; Yue et al., 2019; Wang et al., 2023), climatic variables (e.g., precipitation and temperature) (Gu et al., 2016; Adler et al., 2017), and atmospheric CO_2 concentration (Shi et al., 2013; Mao et al., 2015)—remain inadequately understood. This knowledge gap is particularly critical given the Plateau's transitional climatic conditions and its vulnerability to both natural fluctuations and anthropogenic impacts. Among these factors, precipitation serves as the primary water resource, exerting a direct influence on large-scale ET patterns (Shao et al., 2019). Simultaneously, vegetation exerts a significant influence on ET through mechanisms such as the "pumping effect" of root systems. Nevertheless, fully separating the effects of vegetation dynamics and climate factors to ET remains a topic of considerable debate (Chen et al., 2017; Bai et al., 2019; Jiang et al., 2021). Recent studies have explored the drivers of evapotranspiration (ET) changes in the Loess Plateau region, revealing complex and sometimes divergent findings. Some research has attributed ET trends primarily to climate variability, such as Zhao et al. (2022), who found that rising temperatures and vegetation greening accounted for 45.6% and 31.6% of ET increases, respectively, across the broader Yellow River Basin. In contrast, Wang et al. (2021) utilized high-resolution remote sensing data for the Loess Plateau specifically, and found that vegetation (as indicated by NDVI) explained 61.4% of ET changes, while precipitation showed a surprising negative contribution (−26.3%). Taking a more balanced approach, Li et al. (2021) assigned 68% of ET changes to climate factors (largely precipitation) and 32% to vegetation recovery based on an empirical model. These discrepancies highlight the methodological and spatial-scale challenges in attributing ET trends. Basin-wide analyses may oversimplify regional heterogeneity, as vegetation restoration on the Loess Plateau is concentrated in areas with steeper slopes and bare soil, rather than the flat terrain of the broader Yellow River Basin (Chen et al., 2007). As a result, such differences in topographical and land-cover conditions result in distinct evapotranspiration (ET) response mechanisms across these regions (Fu et al., 2003). Furthermore, even within the Loess

Plateau, localized studies may overemphasize specific conditions or data uncertainties, as demonstrated by Bai et al. (2019), who found that 93% of ET trends could be explained by vegetation (NDVI) in a hilly-gully basin, while attributing only 18.1% to precipitation. These divergent findings reflect the complex, nonlinear interactions between land surface processes and atmospheric conditions in this transitional zone, where both long-term changes and interannual variability play significant roles. Importantly, previous studies have frequently overlooked the distinction between the cumulative effects of long-term trends and the immediate impacts of interannual fluctuations, as well as the separate investigation of the driving mechanisms behind these two types of variability in ET, potentially leading to divergent attribution outcomes. This distinction is critical for characterizing the response of ET to climate and vegetation changes, especially given the temporal dynamics of vegetation recovery, where newly established vegetation may exert a different hydrological influence compared to mature ecosystems.

To address the knowledge gaps identified in previous studies, this research adopted an integrated approach that separately examines long-term trends and interannual variability in evapotranspiration (ET) across the Loess Plateau. The study divided the region into five ecological sub-regions based on different land-use types, and leveraged multiple datasets including the Global Land Evaporation Amsterdam Model (GLEAM) v3 (Miralles et al., 2011; Martens et al., 2017), Normalized Difference Vegetation Index (NDVI) data from the Global Vegetation Health Products (GVHP), and climate reanalysis data from the fifth-generation European Centre for Medium-Range Weather Forecasts (ECMWF) dataset (ERA5) (Hersbach et al., 2023). For long-term trend analysis, the study utilized a simple yet effective method (Huang et al., 2020) to disentangle the respective contributions of vegetation dynamics and climatic factors to ET changes during the growing season. To examine interannual variability, we removed the long-term trends and analyzed the correlations between ET, vegetation activity, and climate factors. By integrating these complementary analytical perspectives, this research provided a comprehensive understanding of the mechanisms driving ET variations in the Loess Plateau. The findings offer valuable insights into the intricate interplay between vegetation restoration and climatic shifts in this transitional climate region.

2 Data and methods

2.1 Data

2.1.1 Evapotranspiration data

This study utilized GLEAM ET data (https://www.gleam.eu/) for the growing season (April to September) from 2000 to 2022 to analyze the spatiotemporal changes in ET on the Loess Plateau. The monthly GLEAM ET data, with a spatial resolution of 0.25° (Miralles et al., 2011; Martens et al., 2017), are subdivided into transpiration (Ec), interception loss (Ei), bare-soil evaporation (Es), snow sublimation (Esn), and open-water evaporation (Ew) (Zhang et al., 2016). For this study, snow sublimation and open-water evaporation were considered negligible for the Loess Plateau during the growing season; thus, only Ec, Ei, and Es were used to calculate ET (Zhang et al., 2019). The GLEAM evapotranspiration data are based on multiple satellite observations, including net radiation, temperature, precipitation, vegetation optical depth, and snow water equivalent. The estimations for Ec and Es are derived from a modified Priestley-Taylor (PT) equation, which calculates them as a function of available energy [net radiation (Rn) minus ground heat flux (G)] and a dimensionless coefficient α representing the parameterized evaporative resistance. Ei is calculated separately using the Gash analytical model of rainfall interception, driven by observations of precipitation and both vegetation and rainfall characteristics. Additionally, this remote-sensing-based dataset accounts for the constraints of soil moisture on evaporation (Priestley and Taylor, 1972) and has been validated as reliable (Song et al., 2023) for assessing the water cycle in semi-arid regions with geographic conditions similar to those of the Loess Plateau.

2.1.2 NDVI data

This study analyzed vegetation changes in the Loess Plateau based on NDVI data with a spatial resolution of 4 km and weekly temporal resolution, obtained from the National Oceanic and Atmospheric Administration (NOAA) Center for Satellite Application and Research (STAR) (https://www.star.nesdis.noaa.gov/smcd/emb/vci/VH/vh_ftp.php). The data have been corrected for atmospheric and geometric distortions to eliminate influences unrelated to vegetation and are widely used in global and regional studies monitoring vegetation dynamics and vegetation responses to climate change (Tang et al., 2020; Zeng et al., 2023). For this study, vegetation changes were analyzed during the same time span as ET, from 2000 to 2022 (April to September). The maximum value compositing (MVC) method was used to synthesize the raw NDVI data into maximum NDVI values (NDVImax) for the growing season, and areas with NDVImax < 0.1 were excluded to avoid potential impacts of soil properties.

2.1.3 Climate data

The monthly precipitation and 2-meter temperature during the growing season (April to September) from 2000 to 2022 were derived from the ERA5 dataset at a resolution of 0.25° × 0.25° (Hersbach et al., 2023). The spatial resolutions of the three aforementioned data sources were aggregated into a common resolution of 0.1° × 0.1° using the bilinear interpolation method.

2.2 Methods

2.2.1 Attribution method of long-term trend in ET

Vegetation changes and climate factors (such as temperature, precipitation, etc.) are the two main driving factors behind the significant trend in ET in the Loess Plateau from 2000 to 2022 (see

Section 3.2). Given the complex interactions among climatic factors, vegetation, and ET, we adopted the method proposed by Huang et al. (2020) to assess the impacts of climate change and vegetation changes on ET and its components. This method assumes that among all pixels showing a significant increasing (or decreasing) trend in ET (or its components), those that also show a significant increasing (or decreasing) trend in vegetation are considered to have their ET changes directly caused by vegetation changes; otherwise, the changes are attributed to other factors. The trends in all variables, including NDVI and ET (and its components), were calculated using two methods: the Mann-Kendall (MK) non-parametric statistical test and least squares estimation. These trends were tested using a T-test to determine the significance level of the trends.

2.2.2 Attribution method of interannual variations in ET

When the long-term trend was removed from the original time series (ET, climatic factors, and NDVI), the detrended time series $y'(i)$ can represent its interannual variability, which can be expressed as:

$$y'(i) = y(i) - (at + b) \tag{1}$$

where $y(i)$ is the original timeseries, i is the time counter (year), a and b are the coefficients using the least square estimation.

After removing the long-term trends, we calculated the interannual correlations between growing season NDVI (or temperature and precipitation) and ET (or its components) at the nearest grid points from 2000 to 2022. The Pearson linear correlation coefficients are expressed as follows:

$$r_{xy} = \frac{\sum_{i=1}^{n}[(x_i - \bar{x})(y_i - \bar{y})]}{\sqrt{\sum_{i=1}^{n}(x_i - \bar{x})^2}\sqrt{\sum_{i=1}^{n}(y_i - \bar{y})^2}} \tag{2}$$

where, x_i is the value of NDVI (or climate factors) for the i th year, and y_i denotes the value of ET (or its components) for the i th year. The significance of the correlation coefficients is test by a T-test (two-tailed).

2.3 Study area

The Loess Plateau (roughly within 34°~41°N, 98°~114°E), with an area of ~632,520 km^2, which accounts for 6.3% of China's total land area (Jiang et al., 2022). The average annual precipitation ranges from 200 mm in the northwest to 800 mm in the southeast, with 60%~70% of the annual precipitation occurring between June and September in the form of high-intensity rainstorms, which often cause extreme soil erosion and drought frequently occurs (Liang et al., 2020). The average annual temperature is 4°C in the northwest and 14°C in the southeast (Peng et al., 2018). Consequently, the region is characterized as a typical transitional zone from an arid to a semi-humid climate, significantly influenced by the East Asian monsoon. The predominant land cover types include grassland, cropland, and forest (Figure 1).

Based on the ecological restoration areas and geographical characteristics of the Loess Plateau, and following the division methods used in previous studies (Jiang et al., 2022; Yang Y. F. et al., 2019), the Loess Plateau is divided into five sub-regions: the Northern Loess Plateau (NLP), the Middle Loess Plateau (MLP), the Eastern Loess Plateau (ELP), the Western Loess Plateau (WLP), and the Southern Loess Plateau (SLP) (Figure 1). Among these, the NLP is a typical semi-arid area with a mean annual precipitation below 400 mm, mostly covered by deserts or desertified land. The MLP is the primary region for vegetation restoration projects (Jiang et al., 2022), while the WLP consists mainly of high tableland and gully regions. The SLP and ELP are primarily composed of broad valley plains and rocky mountain areas.

3 Results

3.1 Climatological pattern of ET on the Loess Plateau

Climatologically, the total growing season ET on the Loess Plateau exhibited a decreasing pattern from southeast to northwest (from > 2 mm/day in the southeast to < 1 mm/day in the northwest), closely mirroring the precipitation pattern and reflecting the limiting role of water resources on the ET process in this semi-humid to semi-arid region (Figure 2A). Among the three components of ET, Ec was the primary contributing component, accounting for ~70% of total ET from 2000 to 2022. Similar to ET, the spatial distribution of Ec (Figure 2B) also showed a decreasing trend from southeast to northwest, with high-value areas exceeding 1.4 mm/day primarily located in semi-humid, forested regions, while low-value areas (<0.6 mm/day) were found in arid to semi-arid regions with precipitation below 200 mm (excluding the Hetao Plain). On the other hand, Ei was substantially lower than Ec (Figure 2C), with rates generally below 0.1 mm/day outside forested areas, contributing minimally to total ET, with values ranging from 3% to 6%.

In contrast to the two vegetation-related ET components (Ec and Ei), the distribution pattern of Es was characterized by low values in the southeast and high values in the northwest (Figure 2D). As the second largest contributor to total ET (~19% to 32%), relatively higher Es values (~1 mm/day) were observed in regions with annual precipitation below 400 mm, where lower vegetation cover allowed Es to dominate the ET process. In comparison, Es in densely vegetated areas was weaker, generally below 0.4 mm/day, indicating a competitive relationship between vegetation water consumption and soil evaporation.

3.2 Change trend in ET on the Loess Plateau from 2000 to 2022

From 2000 to 2022, the regional mean ET time series of the Loess Plateau showed a significant increasing trend ($p < 0.05$)

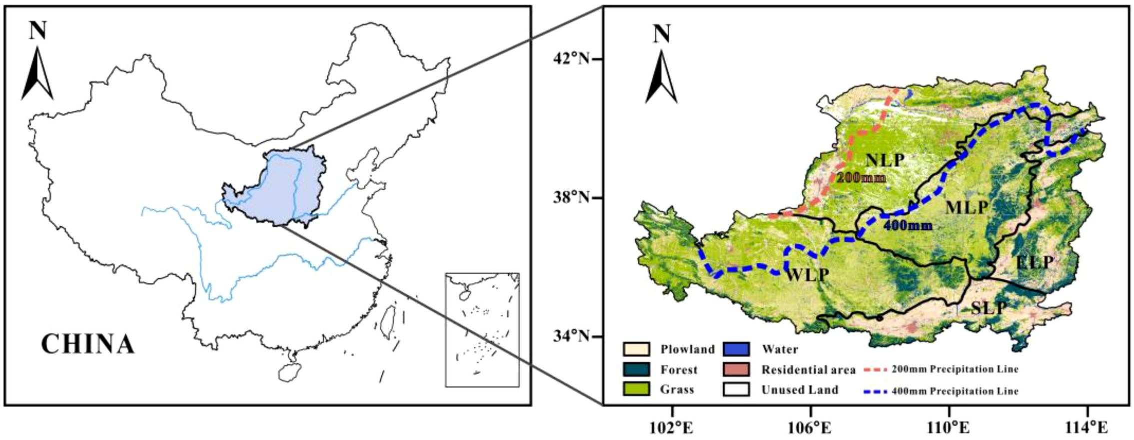

FIGURE 1
Spatial distribution of land use types over the Loess plateau (shading) being divided into five ecological sub-regions (delimited by black lines), and the isolines of mean annual precipitation of 200 mm and 400 mm are also shown in dashed lines. Source: The map was created based on the standard maps provided by the Ministry of Natural Resources Standard Map Service website under GS(2016)1594. No modifications were made to the map boundaries.

(Figure 3A), with an increase rate of 0.164 mm/day per decade (R^2=0.5197). Both vegetation-related components, Ec and Ei, also showed significant increasing trends ($p < 0.05$) with respective increase rates of 0.194 and 0.019 mm/day per decade (Figures 3B, C). In contrast, the regional mean Es demonstrated a significant decreasing trend ($p < 0.05$) over the same period (Figure 3D), with a decrease rate of −0.043 mm/day per decade, partially offsetting the increasing trends of the two vegetation-related components. As a result, the total ET showed a relatively smaller increasing trend compared to Ec.

The distribution of ET change trends indicated that the majority of the Loess Plateau experienced a significant increase in ET from 2000 to 2022, with the exception of marginal areas in the NLP, WLP, SLP, and ELP (Figure 4A). Compared to ET, Ec exhibited a broader area with a significant increasing trend (Figure 4B), particularly in the northwestern and southeastern corners of the

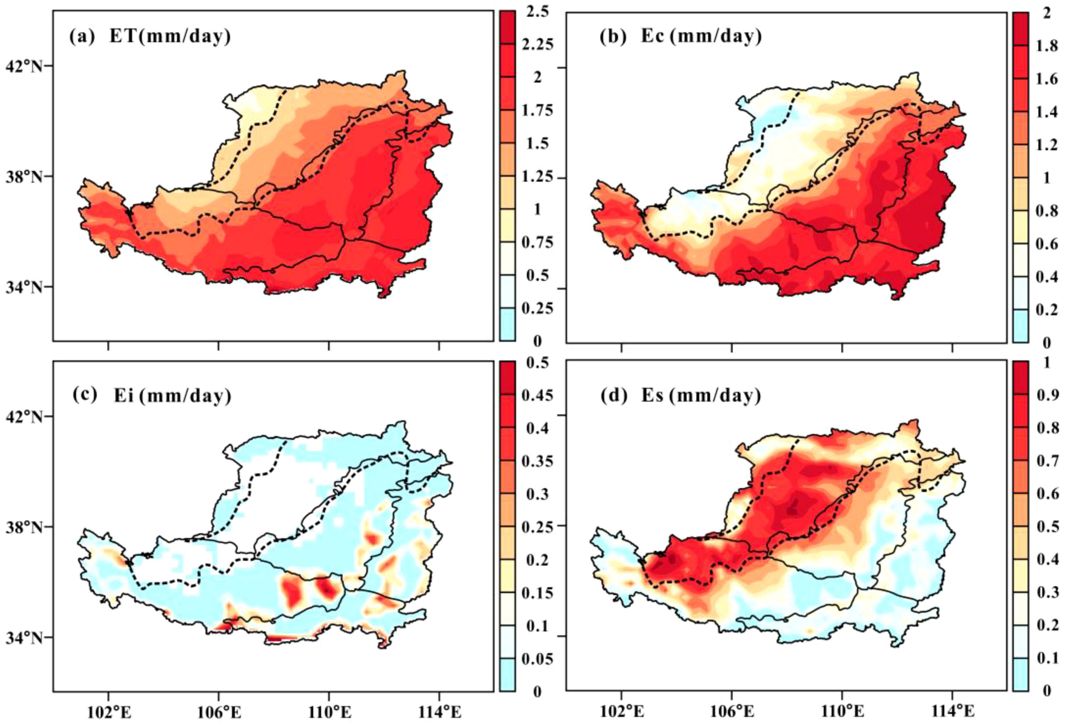

FIGURE 2
Climatological pattern in **(A)** evapotranspiration (ET), **(B)** vegetation transpiration (Ec), **(C)** canopy intercepted water evaporation (Ei), and **(D)** soil evaporation (Es) during the growing season. The dashed and solid lines are the same as that in Figure 1.

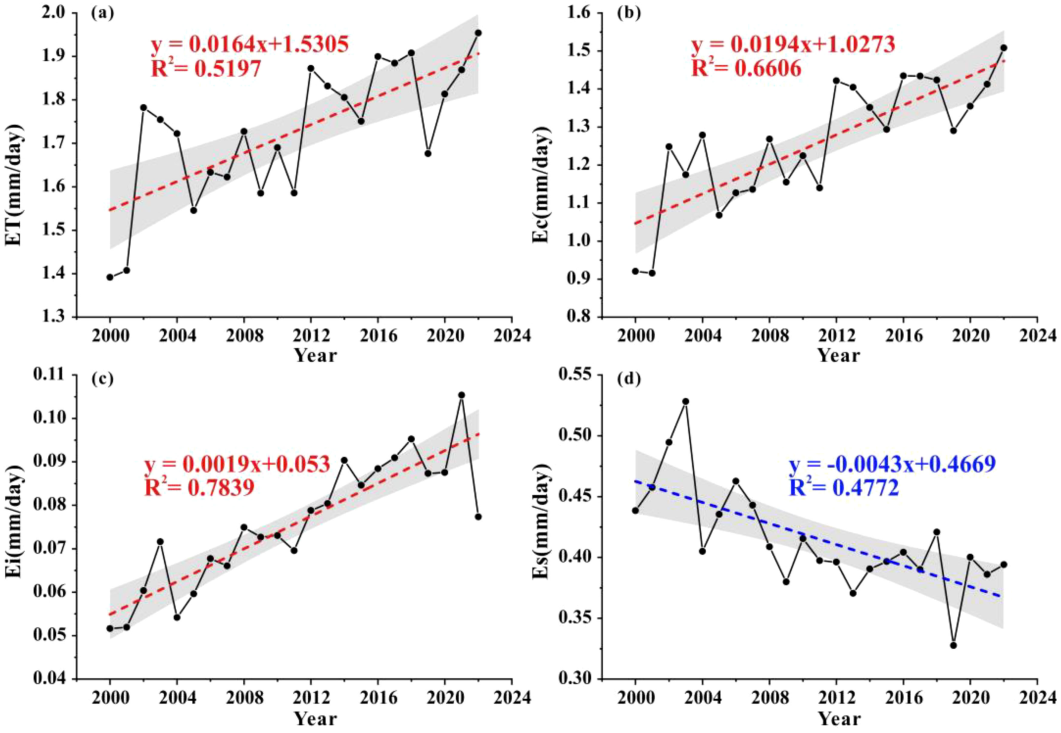

FIGURE 3
Time series of regional mean **(A)** evapotranspiration (ET), **(B)** vegetation transpiration (Ec), **(C)** canopy intercepted water evaporation (Ei), and **(D)** soil evaporation (Es) of the Loess Plateau during the growing season from 2000 to 2022, and their linear regression lines area plotted in dashed lines. The gray shaded area represents the confidence interval for $p < 0.5$.

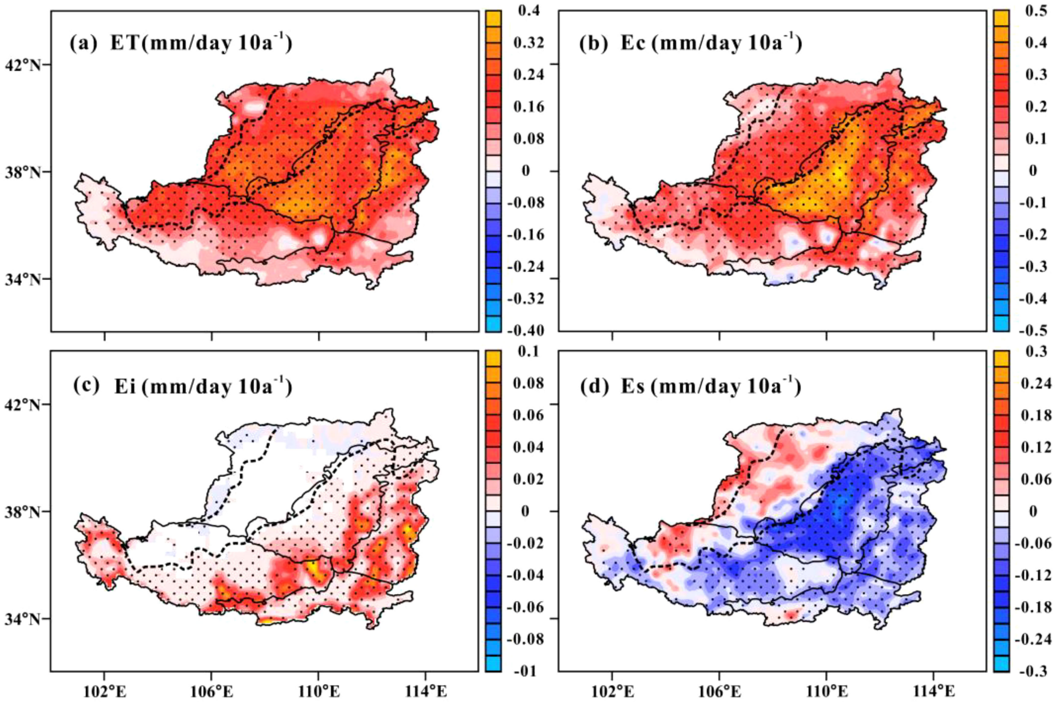

FIGURE 4
Spatial distribution of MK trends in **(A)** evapotranspiration (ET), **(B)** vegetation transpiration (Ec), **(C)** canopy intercepted water evaporation (Ei), and **(D)** soil evaporation (Es) over the Loess Plateau during the growing season from 2000 to 2022. Those areas with significant changes (p < 0.05) are stippled.

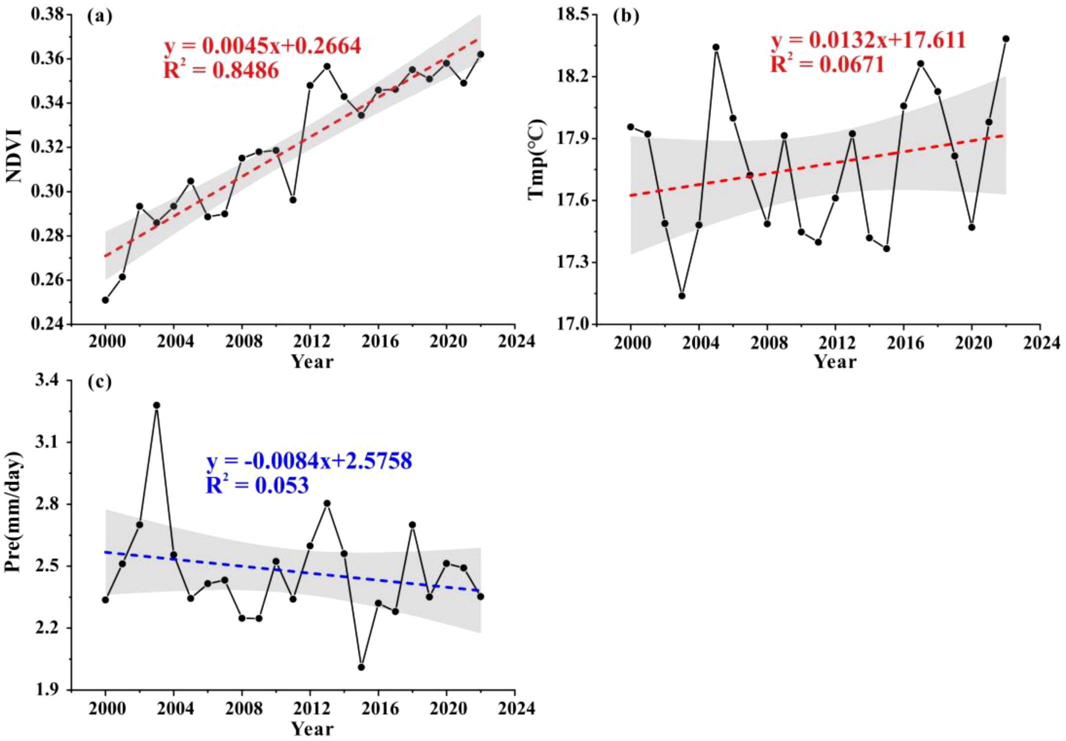

FIGURE 5
Time series of regional mean **(A)** NDVI, **(B)** temperature, and **(C)** precipitation of the Loess Plateau during the growing season from 2000 to 2022. The gray shaded area represents the confidence interval for $p < 0.5$.

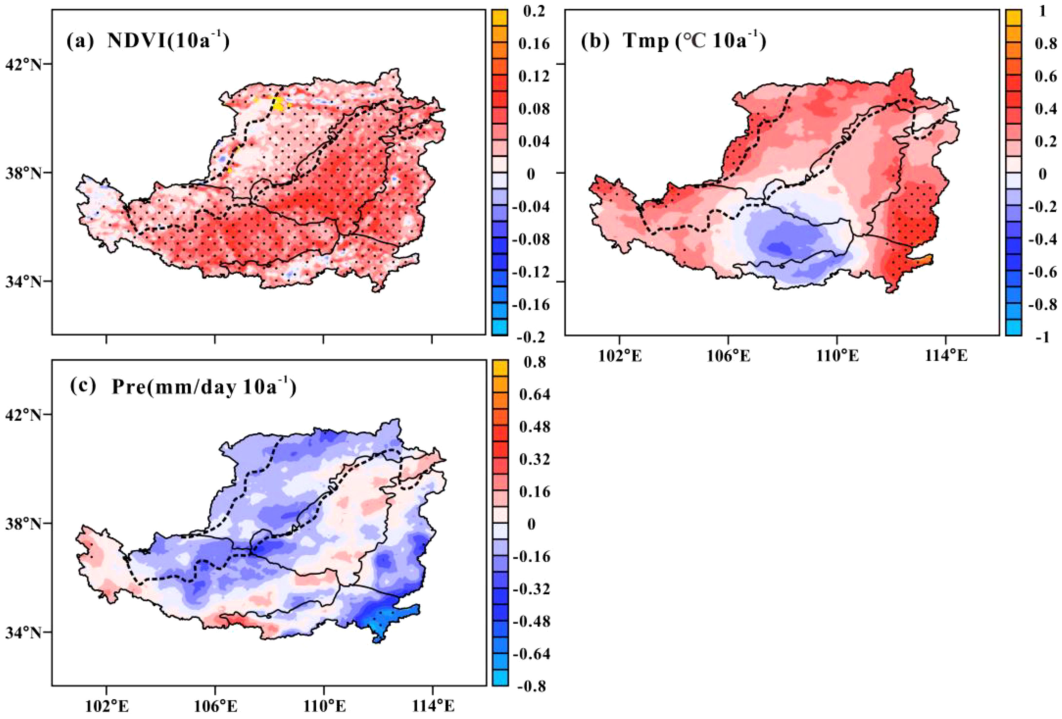

FIGURE 6
MK Trends in **(A)** NDVI, **(B)** temperature, and **(C)** precipitation over the Loess Plateau during the growing season from 2000 to 2022. Stippled areas represent significant changes (p < 0.05).

Loess Plateau. In the MLP, where substantial vegetation recovery occurred, the trend in Ec exceeded that of ET (> 0.5 mm/day per decade). The water intercepted by the vegetation canopy showed a marked increase in the southeastern semi-humid region of the Loess Plateau (MLP, WLP, and ELP) (Figure 4C), with particularly pronounced increasing trends (> 0.1 mm/day per decade) in forested areas. In contrast, Es displayed opposite change trends between the northwestern and southeastern parts of the Loess Plateau (Figure 4D). Most of the Loess Plateau exhibited significant decreasing trends in Es, particularly in the semi-humid MLP, WLP, and ELP, while a minority of areas (primarily in the semi-arid and arid NLP and northern WLP) showed significant increasing trends in Es.

3.3 Changes in NDVI and climatic factors over the Loess Plateau from 2000 to 2022

The regional mean NDVI time series of the Loess Plateau exhibited a significant ($p < 0.001$) increasing trend from 2000 to 2022 (Figure 5A), with an increase rate of 0.045 per decade, indicating an overall greening trend for the Loess Plateau since the implementation of large-scale ecological projects. The spatial pattern of NDVI trends revealed that almost the entire Loess Plateau experienced significant increases in NDVI, particularly in the MLP and WLP regions, where the NDVI increase exceeded 0.1 per decade (Figure 6A). During the same period, the Loess Plateau as a whole did not exhibit significant trends in either temperature or precipitation during the growing season (Figures 5B, C), with change rates of 0.132°C per decade and −0.084 mm/day per decade, respectively. Moreover, the spatial distribution of trends in each pixel did not show significant trends in most areas of the Loess Plateau (Figures 6B, C). Most of the Loess Plateau experienced a rise in temperature from 2000 to 2022, with a declining trend observed only in the eastern WLP and western SLP (Figure 6B). Additionally, there were decreasing trends in precipitation across the majority of the Loess Plateau (Figure 6C), with only parts of the eastern MLP and southern WLP showing non-significant increases in precipitation.

3.4 Attribution of long-term trend in ET over the Loess Plateau

By employing the methodology proposed by Huang, we assessed whether vegetation greening is the direct cause of the trends in ET on the Loess Plateau. Among the pixels showing a significant trend in ET (covering approximately 71.4% of the total area of the Loess Plateau),

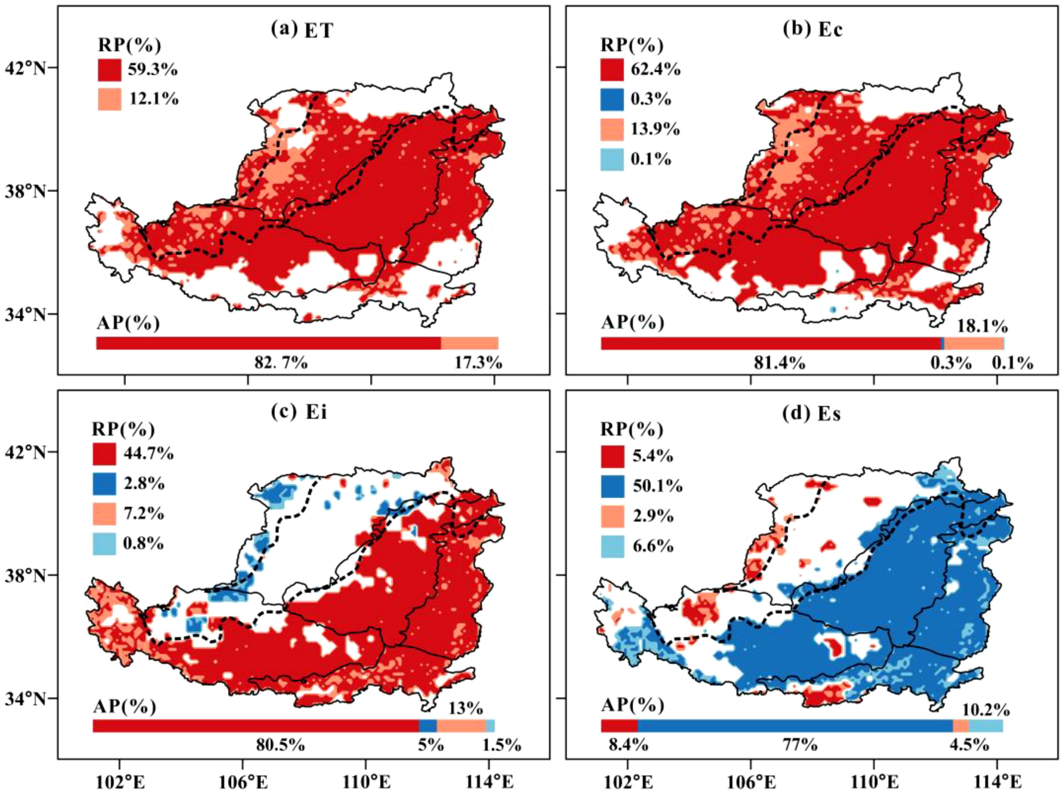

FIGURE 7
The distribution of whether significant trends in **(A)** evapotranspiration (ET), **(B)** vegetation transpiration (Ec), **(C)** canopy intercepted water evaporation (Ei), and **(D)** soil evaporation (Es) are cause directly by NDVI changes: Only pixels with significant increasing (decreasing) ET (and its components) are shown in red (blue), and those also show significant changes in NDVI are shown in dark colors, while those do not show significant NDVI changes are shown in light colors. Absolute Percentage (AP) refers to the percentage of pixels of each color relative to the total number of colored pixels; Relative Percentage (RP) refers to the percentage of pixels of each color relative to the total number of pixels on the Loess Plateau.

around 82.7% also experienced a significant increase in NDVI (Figure 7A), while only about 17.3% did not show any significant change in NDVI. This result indicates that the majority of areas with significant ET changes were directly caused by vegetation greening. Compared to ET, the area with a significant increase in Ec was larger, covering approximately 75.1% of the Loess Plateau (Figure 7B). In areas with significant increases in Ec, over 81.4% of grid points also showed a notable increase in NDVI, suggesting that the rise in Ec is predominantly due to vegetation recovery. Less than 20% of the grid points, primarily located in arid and semi-arid zones, exhibited no significant change in vegetation. There were few pixels with significant decreases in Ec, mainly associated with changes in vegetation cover. Furthermore, approximately 80.5% of all pixels showing a significant increase in Ei also experienced significant rises in vegetation (Figure 7C), indicating that the increase in Ei is mainly driven by vegetation changes. Less than 15% of these areas (primarily in the western WLP and the cropland areas of SLP and ELP) showed Ei enhancement driven by climatic changes. Of the small number of pixels with a significant decrease in Ei in arid and semi-arid regions, about one-fourth of these areas were attributed to vegetation changes.

Between 2000 and 2022, the area with a significant decreasing trend in Es covered approximately 56.7% of the total area of the

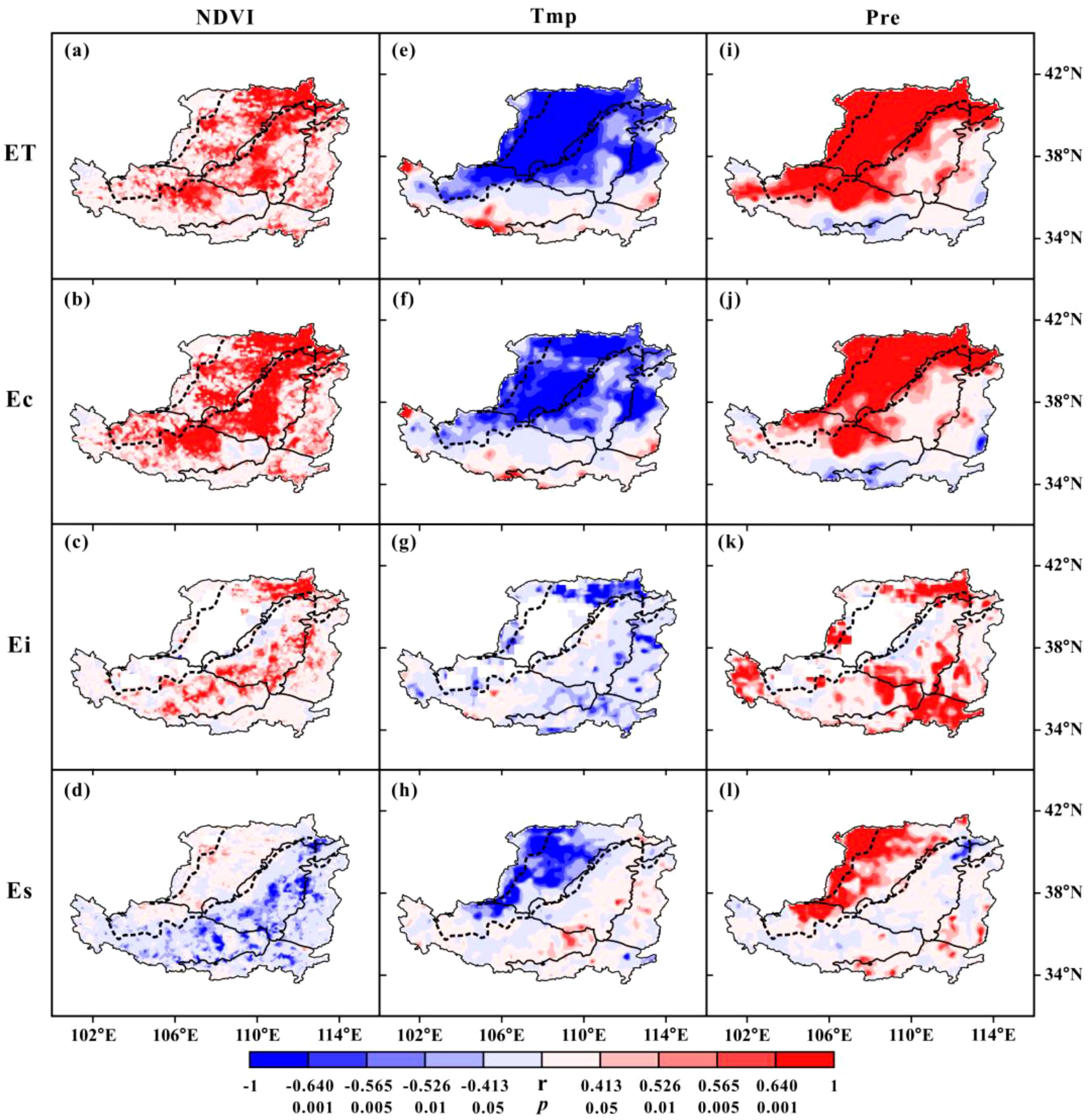

FIGURE 8
Pearson correlation coefficients and their significance levels (two-tailed) between evapotranspiration (ET), vegetation transpiration (Ec), canopy intercepted water evaporation (Ei), and soil evaporation (Es) and (left) NDVI/ (middle) temperature/ (right) precipitation in growing season over the Loess Plateau from 2000 to 2022. The correlation coefficient (*r*) values are shown with the corresponding significance test (*p*-values) below, both sharing the same color bar.

Loess Plateau, primarily distributed across the MLP, ELP, eastern WLP, and parts of the SLP. In these areas, the majority (about 77%) coincided with a significant increase in NDVI (Figure 7D), indicating that the decrease in Es was related to changes in vegetation cover. In addition, about 12.9% of the total area showed a significant increase in Es, sporadically located in arid and semi-arid regions, with approximately 65% of these areas also driven by changes in vegetation cover. Although Es was not directly produced by vegetation, long-term vegetation changes remained a primary cause of the changing trends in Es.

3.5 Attribution of interannual variations in ET over the Loess Plateau

To explore the impact of vegetation conditions and climate factors on ET at an interannual time scale, Pearson correlations between ET (and its components) and NDVI (or climatic factors) were calculated for each pixel after removing their corresponding trend components (Figure 8). The results revealed that ET and Ec were significantly ($p < 0.001$) and positively correlated with NDVI in some areas of the MLP, NLP, and WLP (Figures 8A, B). In contrast, the positive correlation of Ei and the negative correlation of Es were largely insignificant (Figures 8C, D). In comparison, the correlations of ET (Ec and Es) with the two climatic factors were much stronger, particularly in the arid and semi-arid regions (p < 0.001, Figures 8E–G, I–K). For instance, there were significantly negative correlations between temperature and ET/Ec/Es, suggesting that in these water-limited areas, increased temperatures and associated drought stress may inhibit the ET process. Additionally, a significantly positive relationship was found between precipitation and ET/Ec/Es over large areas in the northwest, although some negative correlations were observed in the southeastern marginal regions. The correlations between precipitation and temperature indicated that interannual variations in ET were predominantly controlled by water availability in these water-limited regions, rather than energy availability. These findings also suggest that climate is the primary factor influencing the interannual variations in ET and its components in the arid and semi-arid regions of the Loess Plateau.

To verify the robustness of our results, the China meteorological forcing dataset (CMFD) (Yang K. et al., 2019) were also conducted correlation tests with ET with long term trends excluded, this dataset integrates ground observations and satellite data and are widely proven to have good performance in representing the precipitation and temperature pattern (Yang et al., 2010; He et al., 2020). The results of CMFD demonstrate that the spatial patterns in the correlation of ET with both temperature and precipitation are highly consistent with that of ERA5 (Supplementary Figures S1), implying that the dominant role of these climatic factors in regulating interannual variability in ET is relatively robust among different data sources. Although some researches show certain overestimation of ERA5 precipitation over the Loess Plateau (Jiang et al., 2021), our result suggests this potential overestimation of ERA5 precipitation does not undermine the validity of our conclusions.

4 Discussion

4.1 Validation of the GLEAM ET product

In this study, we employed the remote-sensing-based GLEAM ET product to estimate ET changes in the Loess Plateau, as it explicitly considers the impact of soil moisture, which is a critical limiting factor for evapotranspiration in such a relatively water-limited region (Ferguson and Wood, 2010; Vinukollu et al., 2011). Generally, the GLEAM ET dataset has been proven to perform well in representing both the temporal and spatial variations of total ET and its components across China, particularly during the warm months, when compared with *in situ* observations and other products (Li, 2023; Yao, 2023). From the climatological results of ET over the Loess Plateau, GLEAM shows that canopy transpiration tends to be larger than soil evaporation, which contrasts with some other products (Jiang et al., 2022; Zhao et al., 2022). This difference is likely due to the following reasons. The GLEAM ET model uses a multi-layer soil model to capture soil moisture distribution and its effects on vegetation transpiration, limiting soil evaporation in dry regions while increasing Ec (Miralles et al., 2011; Martens et al., 2017). In contrast, other evapotranspiration models, such as PML and VIC models, which are based on the Penman-Monteith equation, focus primarily on vegetation and meteorological factors, emphasizing energy balance over soil moisture (Liang et al., 1994; Zhang et al., 2019). These models estimate transpiration and evaporation separately via remote sensing, potentially overestimating soil evaporation in areas with sparse vegetation. Differences in meteorological inputs also contribute to the variations in their estimates.

4.2 Uncertainty in attribution of long-term trends using Huang's method

To determine whether long-term changes in vegetation are the direct drivers of observed trends in evapotranspiration (ET) and its components, we applied the method proposed by Huang. This approach posits that if both ET (and its components) and NDVI exhibit significant trends at the same grid point, it can be inferred that vegetation changes are the direct drivers of the trends in ET or its components, regardless of the presence of significant changes in climatic factors. Importantly, the trend in NDVI itself may be influenced by significant trends in climatic factors. However, we do not delve further into whether vegetation changes are attributable to anthropogenic activities or climatic factors, nor do we examine the extent to which climate change indirectly influences ET by altering vegetation conditions. Our analysis focuses exclusively on the direct impact of vegetation changes on ET. Conversely, when a significant trend in ET (or its components) occurs without a corresponding significant trend in NDVI, changes in climatic factors are considered the direct cause. Specifically, this method attributes vegetation changes primarily to anthropogenic activities (e.g., reforestation or land-use changes), while linking changes in climatic factors (e.g., temperature or precipitation) directly to climate change. In reality, the interactions between vegetation, climatic factors (e.g., precipitation and temperature), and ET are highly complex, involving multiple feedback mechanisms, which makes disentangling the relationships among these variables challenging. For example, in the southeastern Loess Plateau, although NDVI exhibited a significant increasing trend, the corresponding increasing trend in Ec may have been offset by the suppressive effects of significantly rising temperatures. Under such stressful conditions, plants may close their stomata, potentially explaining the overall insignificant increase in ET in these areas (Yang Y. et al., 2019). In general, Huang's method provides a robust framework for disentangling the intricate relationships among vegetation dynamics, climatic factors, and ET trends through clear assumptions and logical classification. By avoiding the complexities of deeper causal mechanisms, this method enhances the simplicity and practicality of the analysis. Despite its simplicity, Huang's method effectively evaluates whether vegetation changes are directly responsible for long-term trends in ET.

4.3 Forcing mechanism of vegetation and climatic factors on ET over the Loess Plateau

The growing season of the semi-arid and semi-humid Loess Plateau is characterized by relatively higher temperatures, larger vapor pressure deficits, and abundant solar radiation. Consequently, regional ET is predominantly governed by water availability in the absence of significant human interventions (Magliano et al., 2017). Theoretically, variations in ET are controlled by variations in water supply (i.e., precipitation), given the absence of large river inputs for most areas of the interior Loess Plateau (Jin et al., 2011; Zhang et al., 2017). However, extensive anthropogenic ecological restoration efforts, particularly the annual planting of new vegetation, have increased Ec, resulting in significant upward trends in ET over the past decade. This sustained increase in ET cannot be explained by non-significant trends in climatic factors but is instead attributed to vegetation greening across the plateau. The greening trend has contributed to increasing both total ET and Ec, while simultaneously being associated with a decline in soil evaporation. This decline is not only caused by increased vegetation, which leads to a soil-drying trend through additional water consumption by Ec and Ei (Allen et al., 2017), but also by the diminishing energy available as increased canopy coverage blocks a larger proportion of solar radiation from reaching the soil surface (Duveiller et al., 2018; Jiang et al., 2022).

However, when the linear trends of all variables are removed, climatic factors (precipitation and temperature) exhibit a stronger correlation with the interannual variability in ET and its components across most of the study area, compared to vegetation dynamics. As expected, the positive correlation between precipitation and ET underscores its crucial role in regulating interannual variations in ET in these semi-arid and semi-humid regions. Although rising temperatures can increase potential ET, actual ET tends to decrease. This is likely because, on the one hand, at yearly or shorter time scales, higher temperatures are often associated with lower precipitation and reduced water supply, which in turn limits ET. On the other hand, during the growing season, leaf stomatal conductance tends to close under extreme heat, leading to reduced ET. The interaction and coupling effects of vegetation changes and climate change on ET are complex. Although many studies have attempted to fully disentangle the impacts of vegetation change and climate change on ET, as vegetation also responds to terrestrial ecosystem and climate changes, few studies have focused on the different forcing mechanisms of the long-term trend and interannual variability in ET. Many studies have attempted to disentangle the impacts of vegetation and climate change on evapotranspiration (ET), but few have explored the distinct mechanisms driving its long-term trends and interannual variability. The interactions between vegetation and climate change on ET are inherently complex, as vegetation dynamically responds to changes in ecosystems and climate conditions. These intricate feedbacks among vegetation change, climate change, and ET highlight the need for further research, particularly into the differing drivers of long-term trends and interannual variability.

4.4 Limitations

Although this study separately examined the relative importance of climatic factors and vegetation dynamics on long-term trends and interannual variations in ET, there are still some limitations that should be addressed in future research. First, ET exhibits high spatial heterogeneity due to its strong dependence on underlying surface conditions. However, the available ET product, with its relatively coarse resolution, was not validated against *in situ* ET measurements, which may introduce substantial uncertainties in the ET estimates. Second, the duration of the available data is relatively short (~20 years). While the long-term trend is significant, the attribution results may vary when using data sources with a longer temporal span. Lastly, this study only analyzed the relationship of ET with two primary climatic factors. Other factors, such as atmospheric CO2 concentration, vapor pressure deficit, and sunshine duration, may also influence ET in the Loess Plateau. Although their impacts may be relatively minor, further research is necessary to comprehensively incorporate a broader range of influencing factors in the future.

5 Conclusions

In this study, we investigated the forcing mechanisms of climatic factors and vegetation dynamics in regulating the long-term trends and interannual variations in ET and its components. The results demonstrate that water resources (precipitation) play a fundamental constraining role in the overall distribution pattern of ET on the Loess Plateau. However, precipitation alone does not fully account for the significant increasing trend in total ET and Ec observed since the implementation of vegetation restoration projects. In contrast, the NDVI shows an increasing trend across most of the Loess Plateau, which may serve as the direct driving force behind the significant trends in ET and its components from 2000 to 2022. Excluding the long-term trend, interannual variability appears to be more closely correlated with climatic factors. The significantly positive relationship between precipitation and ET underscores ET's heavy reliance on water resources in these regions, while the significantly negative correlation with temperature ($p < 0.001$) suggests a warming-induced drought stress effect on ET and its components in the arid and semi-arid regions of the Loess Plateau.

Additionally, our research reveals another intriguing finding: since 2012, the NDVI on the Loess Plateau has plateaued after a period of rapid increase, which aligns with existing studies indicating that the artificial greening of the Loess Plateau may have reached the limits of its environmental carrying capacity. This suggests that as vegetation greening approaches its peak, future ET on the Loess Plateau will be predominantly influenced by climate change. Given the insignificant fluctuations in precipitation, the warming trend is expected to dominate interannual variations in ET, leading to broader soil drying and water resource shortages. These changes will consequently impact the sustainable development of local agriculture and substantially increase the financial investment and costs required by the local government to maintain the current ecosystem. Therefore, it is essential to strike a balance between the limits of vegetation greening and financial investment under future warming scenarios. Our study provides insights into how ET and its components change under current ecological restoration projects on the Loess Plateau and offers a scientific basis for understanding the response processes of the hydrological cycle to large-scale vegetation greening and for regional water resource security assessment.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary Material. Further inquiries can be directed to the corresponding author.

Author contributions

QT: Conceptualization, Data curation, Formal Analysis, Investigation, Methodology, Resources, Software, Validation, Visualization, Writing – original draft, Writing – review & editing. TH: Conceptualization, Data curation, Funding acquisition, Methodology, Project administration, Supervision, Visualization, Writing – review & editing. HZ: Software, Validation, Visualization, Writing – review & editing. PZ: Software, Validation, Writing – review & editing.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Generative AI statement

The author(s) declare that no Generative AI was used in the creation of this manuscript.

Publisher's note

Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fevo.2025.1513189/full#supplementary-material

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