# Trend and future persistence of leaf area index across transboundary river basin landscapes in Central Asia

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## Abstract

The middle and lower reaches of the Irtysh River form a transboundary ecological corridor across the Republic of Kazakhstan and Russia and represent an environmentally sensitive region in arid Central Asia. Understanding long-term vegetation dynamics in this region is essential for evaluating ecological stability and supporting cross-border ecosystem management. However, existing studies are mostly confined to individual administrative units, breaking the eco-hydrological integrity of transboundary basins; meanwhile, most analyses rely on single annual-mean vegetation metrics, failing to reveal the differentiated variation patterns and long-term persistence of LAI across different vegetation growth states. This study used the Global Inventory Modeling and Mapping Studies Leaf Area Index 4g (GIMMS LAI4g) dataset and Climate Research Unit (CRU) precipitation data from 1982 to 2020, to investigate the spatiotemporal dynamics of leaf area index (LAI) across 14 transboundary subregions in the middle and lower reaches of the Irtysh River Basin. Specifically, this study applied Mann-Kendall trend analysis and Theil-Sen median slope estimator to identify long-term trends, employed rescaled range analysis to evaluate long-term persistence, conducted Pearson correlation analysis to quantify the relationship between LAI and precipitation, and used spatial pattern analysis to characterize regional heterogeneity. The results showed significant increases in annual mean and maximum LAI, with Sen' s slopes of 0.0025/a and 0.0077/a, respectively, whereas annual minimum LAI exhibited a significant decreasing trend (-0.0011/a). Pronounced spatial heterogeneity was observed among mountainous and piedmont regions, steppe–riparian transition zones, and downstream forest-wetland landscapes. Rolling-window analysis revealed relatively stable vegetation dynamics during the early period, followed by enhanced spatial divergence and increased interannual variability after the early 2000s. All LAI indicators exhibited strong persistence, with Hurst exponents exceeding 0.7000 across the study area, indicating that the observed vegetation trajectories are likely to persist in the future. Precipitation showed significant positive correlations with annual maximum and mean LAI in 64.29% and 57.14% of the study area, respectively, whereas annual minimum LAI showed generally weak responses to precipitation variability. These findings improve understanding of vegetation dynamics and future persistence in transboundary arid river basins and provide scientific support for ecological conservation and sustainable watershed management in Central Asia.


## Full Text

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# Trend and future persistence of leaf area index across transboundary river basin landscapes in Central Asia

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**Abstract:** The middle and lower reaches of the Irtysh River form a transboundary ecological corridor across the Republic of Kazakhstan and Russia and represent an environmentally sensitive region in arid Central Asia. Understanding long-term vegetation dynamics in this region is essential for evaluating ecological stability and supporting cross-border ecosystem management. However, existing studies are mostly confined to individual administrative units, breaking the eco-hydrological integrity of transboundary basins; meanwhile, most analyses rely on single annual-mean vegetation metrics, failing to reveal the differentiated variation patterns and long-term persistence of LAI across different vegetation growth states. This study used the Global Inventory Modeling and Mapping Studies Leaf Area Index 4g (GIMMS LAI4g) dataset and Climate Research Unit (CRU) precipitation data from 1982 to 2020, to investigate the spatiotemporal dynamics of leaf area index (LAI) across 14 transboundary subregions in the middle and lower reaches of the Irtysh River Basin. Specifically, this study applied Mann-Kendall trend analysis and Theil-Sen median slope estimator to identify long-term trends, employed rescaled range analysis evaluate long-term persistence, conducted Pearson correlation analysis to quantify the relationship between LAI and precipitation, and used spatial pattern analysis to characterize regional heterogeneity. The results showed significant increases in annual mean and maximum LAI, with Sen' s slopes of 0.0025/a and 0.0077/a, respectively, whereas annual minimum LAI exhibited a significant decreasing trend (-0.0011/a). Pronounced spatial heterogeneity was observed among mountainous and piedmont regions, steppe-riparian transition zones, and downstream forest-wetland landscapes. Rolling-window analysis revealed relatively stable vegetation dynamics during the early period, followed by enhanced spatial divergence and increased interannual variability after the early 2000s. All LAI indicators exhibited strong persistence, with Hurst exponents exceeding 0.7000 across the study area, indicating that the observed vegetation trajectories are likely to persist in the future. Precipitation showed significant positive correlations with annual maximum

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and mean LAI in 64.29% and 57.14% of the study area, respectively, whereas annual minimum LAI showed generally weak responses to precipitation variability. These findings improve understanding of vegetation dynamics and future persistence in transboundary arid river basins and provide scientific support for ecological conservation and sustainable watershed management in Central Asia.

**Keywords:** leaf area index (LAI); vegetation; spatiotemporal variation; precipitation; human activity; Irtysh River Basin; Central Asia

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# 1 Introduction

Vegetation is a core component of terrestrial ecosystems, maintaining carbon cycles, regulating hydrological processes, and mitigating the impacts of climate change (Yin et al., 2017; Xia et al., 2022). Changes in vegetation cover and productivity reflect regional ecological conditions and record the combined influences of climate variability and anthropogenic disturbances (Piao et al., 2011). Under global warming, changes in precipitation patterns and water availability in arid and semi-arid areas may further increase ecosystem vulnerability. Vegetation in these areas is highly sensitive to water availability and has become a key research focus at the intersection of ecology, geography, and hydrological modeling (Yin et al., 2017).

Remote sensing technology provides a reliable means for long-term and large-scale vegetation monitoring. The normalized difference vegetation index (NDVI) is widely used but is easily affected by soil background and atmospheric effects, making it difficult to accurately characterize vegetation' s photosynthetic capacity and biomass (Tucker et al., 2005; Harris et al., 2020). In comparison, the leaf area index (LAI) directly reflects the leaf projection area per unit surface. It is more suitable for distinguishing the productivity differences among artificial oases, natural wetlands, and grasslands in arid areas. LAI therefore provides an important indicator for investigating vegetation productivity and vegetation-water interactions in arid and semi-arid areas (Harris et al., 2020; Cao et al., 2023).

Numerous studies have confirmed that precipitation dominates vegetation dynamics in arid areas of Central Asia, and its impact is far greater than that of temperature and sunshine duration (Yue et al., 2002; Yin et al., 2017). However, two major limitations remain in current understanding. On the one hand, existing studies are mostly limited to a single administrative region, which destroys the integrity of transboundary watersheds. Transboundary rivers are complete natural geographical units, with continuous hydrological connectivity, zonal vegetation distribution, and cross-border transmission of human interference. However, previous studies usually take national boundaries as their scope of study and artificially split the entire watershed. This practice not only ignores the cross-border impacts of upstream reservoir operations, transboundary water transfers, and land-use change on downstream vegetation but also fails to capture vegetation response characteristics under the cross-border climate transition (from arid to semi-humid). As a result, the conclusions obtained are fragmented and one-sided, unable to reflect the overall pattern of vegetation changes in the basin and to support the practical needs of transboundary ecological protection and water resource coordination (Liu et al., 2022; Li et al., 2024b). On the other hand, existing studies adopt overly simplified interannual scales that ignore the distinct characteristics of LAI indicators and interannual fluctuation patterns. Previous studies have often relied on annual mean vegetation indices or single LAI metrics for analysis, without distinguishing the differential characteristics of variation in mean, maximum, and minimum LAI, and failed to identify the phased evolution law of interannual LAI fluctuations. The single overall interannual scale further weakens the ability to reveal the coupling relationship between static features and interannual LAI changes, making it impossible to accurately quantify the persistence and future trend stability of different LAI indicators.

The middle and lower reaches of the Irtysh River span the Republic of Kazakhstan (hereinafter referred to as Kazakhstan) and Russia, forming an ecologically sensitive transboundary corridor characterized by a hydroclimatic gradient from semi-arid steppe regions in the middle reaches to relatively humid forest-wetland landscapes in the lower reaches (Xia et al., 2022). The middle reaches in Kazakhstan have a temperate continental arid climate, with annual precipitation of 150–300 mm and high evaporation rates, where vegetation is dominated by irrigated agriculture and riparian forests (Li et al., 2008; Yang et al., 2012). The lower reaches in Russia have a temperate semi-humid climate, with natural wetlands, broad-leaved forests, and grasslands as the main vegetation types (Yin et al., 2017; Liu et al., 2022). In dryland areas, engineering measures such as check dams and reservoirs can reshape groundwater recharge and improve vegetation water supply conditions (Li et al., 2024b). Affected by climate warming, water conservancy projects, and agricultural development, vegetation in the Irtysh River Basin exhibits significant spatial heterogeneity, yet the mechanisms driving this heterogeneity remain unclear (Yue et al., 2002; Nemani et al., 2003).

At present, socio-hydrological research has shifted from theoretical analysis to practical water resource management, emphasizing the coordinated governance of natural processes and human activities in transboundary basins (Sivapalan et al., 2012). However, the long-term spatiotemporal variation, persistence characteristics, and precipitation response mechanism of LAI in the middle and lower reaches of the Irtysh River have not been systematically analyzed, and the two shortcomings in previous studies remain unresolved.

Therefore, this study focused on the transboundary middle and lower reaches of the Irtysh River Basin and used the Global Inventory Modeling and Mapping Studies Leaf Area Index 4g (GIMMS LAI4g) dataset (1982–2020) (Cao et al., 2023; Cao and Zhu, 2024) and Climate Research Unit (CRU) precipitation data. Mann-Kendall trend analysis and Sen’ s slope estimation were applied to identify long-term LAI trends, rescaled range analysis was used to quantify the long-term persistence and temporal stability of LAI (Mandelbrot and Wallis, 1969; Yue et al., 2002), and Pearson correlation analysis was employed to evaluate the relationship between LAI and precipitation. The objectives are: (1) to reveal the spatiotemporal variation and mutation characteristics of LAI in 14 transboundary subregions in the middle and lower reaches of the Irtysh River Basin in Central Asia from 1982 to 2020; (2) to quantify the long-term persistence of LAI and assess trend stability; (3) to analyze the response of LAI to precipitation variability. The results can provide scientific support for transboundary ecological protection, water resource coordination, and sustainable vegetation management in arid Central Asia (Zhang et al., 2021; Li et al., 2023; Li et al., 2024a).

## 2 Study area

This study focused on the transboundary middle and lower reaches of the Irtysh River (46°49$ ‘36’ ‘–61°58’ 28’ ‘*N*, 58°56’ 46’ ‘–87°18’ 49’’ $E), which stretches across northeastern Kazakhstan and the southern West Siberian Plain of Russia. As the largest tributary of the Ob River system, the Irtysh River originates from the Altay Mountains in Xinjiang Uygur Autonomous Region, China, flows northwest through Kazakhstan and Russia, and finally joins the Ob River near Khanty-Mansiysk Autonomous Okrug, Russia. The river has a total length of approximately 4248 km and a drainage area of 1.643 × 10^6 km^2 (Li et al., 2008). The study area covers a continuous environmental gradient from dry mountainous and steppe ecosystems in the southeast to humid forest-wetland ecosystems in the northwest, making it a sensitive region for investigating vegetation responses to climatic variability and hydrological changes in Central Asia (Yin et al., 2017; Zhang et al., 2021).

### 2.1 Division of upper, middle, and lower reaches

The upper reach of the Irtysh River runs from the headwater in the Altay Mountains to the section near Semey City (50°25$ '12' '$N, 80$°15' 36'' $E), the former Semipalatinsk City in Kazakhstan. This section is dominated by alpine valleys and gorges, receives abundant orographic precipitation and

glacial meltwater recharge, and serves as the core runoff generation zone of the basin. The Bukhtarma Reservoir located in this reach exerts strong multi-year regulation on downstream discharge (Li et al., 2024b). The middle reach extends from the section near Semey City to Omsk City in Russia (54°59$ '24' '$N, 73$°22' 12" $E) and flows through the Kazakh Hills and the southern edge of the West Siberian Plain. Channels in this sectio termagricultural development (Liu et al., 2022). The lower reach stretches from the section near Omsk City to the co MansiyskCity (60°59' 24' '$N, 69$°01' 48'' $E), and meanders across the West Siberian Plain with extremely flat terrain interspersed with extensive floodplains, swamps, and peatlands. Multiple large tributaries join the main stream in this reach and lead to a sharp increase in discharge, which forms a complex and stable forest-wetland ecosystem (Li et al., 2024b). This study focused on the middle and lower reaches from the section near Semey City to the Ob River confluence, and we divided the basin into 14 functional subregions (Zones 1–14) by integrating digital elevation model (DEM) data, administrative boundaries, and hydro-climatic zoning information, as shown in Figure 1a.

**Fig. 1** Overview of the middle and lower reaches of the Irtysh River Basin. (a), elevation distribution of the study area; (b), spatial distribution of annual precipitation in 2018; (c), vegetation cover map of 2020. Numbers 1–14 are the subregion serial numbers. DEM, digital elevation model.

## 2.2 Topographical and climatic characteristics

The middle and lower reaches of the Irtysh River exhibit a distinct southeast-northwest environmental gradient. Elevation decreases from the Altay foothills in the southeastern part of the study area toward the flat West Siberian Plain in the northwest. Zone 13 represents the high-altitude mountainous transition zone in the eastern part of the study area, with elevations ranging from approximately 1500 to 3750 m. Zones 3, 4, 9, and 12 consist mainly of piedmont plains and transitional mountain–steppe landscapes, with elevations generally between 500 and 1500 m. The remaining zones are distributed across low-altitude plains and floodplain areas, where elevations are mostly below 500 m and the terrain is characterized by extensive alluvial plains, wetlands, and local depressions (Liu et al., 2022).

The climate of the region is strongly influenced by continental circulation, Atlantic moisture transport, and the Siberian High, resulting in a pronounced precipitation gradient. Annual

precipitation gradually increases from the southeastern mountainous and steppe regions (approximately 157–375 mm) toward the northern and northwestern lowlands (approximately 375–700 mm) (Fig. 1b). The relatively dry southeastern regions are dominated by steppe, shrubland, and sparse vegetation, whereas wetter downstream areas support forest, meadow, and wetland ecosystems. This spatial hydro-climatic gradient provides an ideal natural framework for examining the effects of climate variability on vegetation dynamics.

## 2.3 Hydrological characteristics and major tributaries

The Irtysh River serves as the primary hydrological artery of the basin, with runoff mainly recharged by glacial meltwater, orographic precipitation, and seasonal snowmelt. The annual runoff distribution is uneven, with the flood season concentrated from May to September and the freezing period lasting approximately 5–6 months from November to April of the following year (Li et al., 2008; Yang et al., 2012). Along the middle and lower reaches, three major first-order tributaries shape the regional hydrological patterns and support distinct vegetation landscapes, namely the Ishim River, Tobol River, and Om River (Li et al., 2008).

The Ishim River is the longest left-bank tributary of the Irtysh River, with a total length of 2450 km and a drainage area of $1.770 \times 10^5$ km$^2$. It originates from the northern edge of the Kazakh Hills, flows northwest through central Kazakhstan and then turns north into Russia, and finally joins the main stream of the Irtysh River near Ust-Ishim Settlement (57°40$ ‘48’ ‘$N, 71°20’ 24’ ’ $E). The river is mainly recharged by spring snowmelt, with an average annual discharge of 83.1 m$^3$/s near the estuary. Its basin covers typical steppe and forest-steppe landscapes, corresponding to Zones 3, 4, and 5 in this study, and the widespread floodplain wetlands along the river provide stable groundwater support for riparian meadow vegetation and buffer seasonal drought stress (Li et al., 2024b).

The Tobol River is the largest left-bank tributary of the Irtysh River in terms of water volume, with a total length of 1591 km and a drainage area of $4.260 \times 10^5$ km$^2$. It originates from the Torghay Plateau in northwestern Kazakhstan, flows northeast across the West Siberian Plain, and joins the Irtysh River near Tobolsk City, Russia (58°09$ ‘14’ ‘$N, 68°12’ 55’’ $E). The river is mainly recharged by snowmelt and summer precipitation, with an average annual discharge of 805.0 m$^3$/s at the estuary. Its basin spans typical steppe, forest-steppe, and boreal forest zones, corresponding to Zones 1 and 2 in the lower reach of this study, and the extensive lake-wetland system in its basin maintains high ecological stability and provides continuous water supply for downstream forest ecosystems (Liu et al., 2022).

The Om River is a right-bank tributary at the end of the middle reach of the Irtysh River, with a total length of 1091 km and a drainage area of 52,600 $km^2$. It originates from the southeastern edge of the Vasyugan Plain, flows southwest through the Baraba Steppe, and joins the main stream near Omsk City (54°59$ '24' '$N, 73°22' 12'' $E). The river is dominated by snowmelt recharge, with an average annual discharge of about 64.0 $m^3/s$ in the lower reach. It corresponds exclusively to Zone 6 in this study, and maintains hydrological connectivity of riparian wetlands while regulating soil moisture conditions for herbaceous and woody vegetation in the transition zone from middle to lower reaches (Yang et al., 2012).

The middle reaches extend from the Semey City section to Omsk City, covering Zones 3, 4, and 9–13. This segment is the core runoff-regulation zone of the basin, where reservoir operations and agricultural irrigation withdrawals significantly modify the natural hydrological rhythm and modulate water availability for riparian vegetation and floodplain ecosystems (Li et al., 2024b). Spatially, Zones 12 and 13 are located in the upper part of the middle reaches near the Semey City section, corresponding to mountainous and piedmont landscapes; Zones 3, 4 and 9 are distributed in the piedmont plain of the Kazakh Hills, belonging to the central part of the middle reaches; Zones 10 and 11 lie along the main stem near the Omsk City section, forming the lower boundary of the middle reaches.

The lower reaches stretch from Omsk City to the confluence with the Ob River, including Zones 1, 2, 5–8, and 14. This segment is dominated by extensive floodplain-wetland complexes, and these ecosystems have strong water-retention capacities that provide a critical buffer against seasonal

drought stress for local vegetation (Liu et al., 2022; Li et al., 2024b). In terms of tributary attribution: the Tobol River basin (Zones 1 and 2) is entirely situated in the lower reaches; the Ishim River spans both the middle and lower reaches, with its upper-middle section (Zones 3 and 4) falling into the middle reaches and its lower estuary section (Zone 5) belonging to the lower reaches; the Om River basin (Zone 6) is located at the starting point of the lower reaches, forming a transitional landscape between the middle and lower reaches.

## 2.4 Vegetation and land use characteristics

Vegetation and land use patterns in the middle and lower reaches of the Irtysh River exhibit clear spatial differentiation along the regional hydro-climatic gradient. Different from the hydrological reach division based on Semey City and Omsk City nodes, we classified the 14 zones into three ecological groups according to dominant vegetation types, precipitation conditions, and landscape characteristics (Fig. 1c).

The mountainous and piedmont steppe zone includes Zones 3, 4, 9, 12, and 13. These subregions are mainly distributed in the southeastern part of the study area and are characterized by relatively low precipitation, complex terrain, and extensive grassland, shrubland, and barren land. Vegetation growth is strongly restricted by water availability and climatic conditions, whereas agricultural irrigation has altered vegetation dynamics in some piedmont areas (Yin et al., 2017; Liu et al., 2022).

The central steppe-riparian transition zone consists of Zones 5, 7, 10, and 11. This region is located mainly along the middle reaches of the Irtysh River and represents a transition between semi-arid steppe and humid lowland ecosystems. Grassland, meadow, and agricultural landscapes are widely distributed, and vegetation dynamics are jointly controlled by precipitation variability, river hydrological processes, and groundwater conditions (Li et al., 2024a).

The lowland forest-wetland zone comprises Zones 1, 2, 6, 8, and 14. These subregions are mainly located in the northern and downstream parts of the study area and receive relatively abundant precipitation. Forests, wetlands, floodplains, and meadow ecosystems dominate this zone, where vegetation growth is strongly associated with moisture availability, hydrological connectivity, and regional climatic variability (Yin et al., 2017; Li et al., 2024b).

# 3 Data and methods

## 3.1 Data sources

This study utilized three primary types of geospatial data, namely LAI, climatic precipitation, and DEM data, supplemented with administrative boundaries and river network data for spatial analysis. All data preprocessing workflows were jointly implemented using ArcGIS Desktop v.10.8.2 (Environmental Systems Research Institute (ESRI), Redlands, USA) and Python programming to ensure efficiency and accuracy. The GIMMS LAI4g dataset (1982–2020) (Cao et al., 2023; Cao and Zhu, 2024) with a native resolution of 1/12° (approximately 0.0833°) was adopted as the vegetation indicator, which has been officially processed with radiometric calibration, atmospheric correction, cloud and snow contamination removal, volcanic aerosol correction, and multi-sensor consistency harmonization, requiring no additional preprocessing for radiation and atmosphere in this study. The dataset is provided by National Cryosphere Desert Data Center (https://www.ncdc.ac.cn). The Climatic Research Unit Time-Series (CRU TS) v. 4.09 Monthly High-Resolution Gridded Multivariate Climate Dataset (1901–2024) with a native resolution of 0.5000°, which has been officially processed through station quality control, grid interpolation, and anomaly correction, was used for climatic analysis (Harris et al., 2020). The DEM dataset, derived from the Shuttle Radar Topography Mission (SRTM), has a native resolution of 0.1000°(×)0.1000°, as shown in the ArcGIS layer properties. For unified spatial analysis, all continuous raster data (LAI, precipitation, and DEM) were resampled to a consistent resolution of 0.1000°(×)0.1000° using bilinear interpolation, which effectively preserves the spatial gradient characteristics of continuous geographic variables; categorical vector data (administrative boundaries and river networks) were matched to the raster grid without distortion. Area-weighted

zonal statistics were applied across the 14 subregions to extract LAI and precipitation indicators. Specifically, pixel values were weighted by their area proportions within each subregion to ensure calculation accuracy. All data were clipped to the boundary of the transboundary middle and lower reaches of the Irtysh River and unified into a common coordinate system to ensure spatial consistency for subsequent trend analysis and spatial differentiation research. In this study, the GLC_FCS30-2020 global 30 m fine land cover dataset published by Aerospace Information Research Institute, Chinese Academy of Sciences was adopted as the fundamental land cover data (Liu and Zhang, 2021). Derived from long-term Landsat time-series remote sensing data, this dataset contains 29 land cover types and satisfies the demand for long-term land surface dynamic monitoring. The dataset is publicly accessible for academic research with no commercial permission, and the data source is formally cited throughout this study.

## 3.2 Methods for analyzing the spatiotemporal variation of LAI

We applied five complementary analytical approaches to systematically quantify the long-term trends, persistence characteristics, precipitation responses, and spatial heterogeneity of LAI across the basin. The Mann-Kendall trend test coupled with the Sen' s slope estimator identifies the direction and magnitude of long-term LAI changes; rescaled range analysis evaluates long-term persistence and future trend stability via the Hurst exponent; Pearson correlation analysis quantifies the linear relationship between LAI and annual precipitation; and spatial pattern analysis characterizes the spatial distribution of interannual LAI variability. We set a uniform significance level of $\alpha$=0.05 for all statistical tests in this study.

### 3.2.1 Mann-Kendall trend test

The Mann-Kendall trend test is a nonparametric statistical method that requires no assumption of normal distribution and exhibits strong robustness against outliers, making it widely applicable for trend detection in hydrological and ecological time series (Yue et al., 2002).

For an LAI time series $\{x_t\}$ ($t$=1, 2, ⋯, $n$) with total length $n$ ($n$=39 in this study), the rank statistic $S$ is defined as:

$$S = \sum_{k=1}^{n-1} \sum_{j=k+1}^{n} sign(x_j - x_k), \qquad (1)$$

where $x$ is the leaf area index; $t$ is the serial number of the year in the time series; $x_t$ is the LAI value in year $t$; and $x_j$ and $x_k$ are the sequential LAI values in years $j$ and $k$ ($j > k$), respectively. The sign function takes the following piecewise form:

$$\text{sign}(\theta) = \begin{cases} 1, \theta > 0 \\ 0, \theta = 0, \\ -1, \theta < 0 \end{cases} \qquad (2)$$

where $\theta$ is the input of the sign function, i.e., $x_j - x_k$.

When the sample size $n \geq 10$, the statistic $S$ approximately follows a normal distribution with an expected value $\mathbb{E}(S) = 0$. The variance of $S$ is calculated as:

$$\text{var}(S) = \frac{n(n-1)(2n+5) - \sum_{k=1}^{m} t_k(t_k - 1)(2t_k + 5)}{18}, \qquad (3)$$

where $m$ is the number of tied groups in the time series; and $t_k$ is the number of elements in the $k^{th}$ tied group.

The standardized test statistic $Z$ is then derived as:

$$Z = \begin{cases} \frac{S-1}{\sqrt{\text{var}(S)}}, S > 0 \\ 0, S = 0 \\ \frac{S+1}{\sqrt{\text{var}(S)}}, S < 0 \end{cases} . \qquad (4)$$

At the significance level $\alpha = 0.05$, a time series shows a statistically significant trend if $|Z| > 1.96$. A positive $Z$ indicates an increasing trend, while a negative $Z$ indicates a decreasing trend.

We further used the Theil-Sen median slope estimator to quantify the magnitude of the LAI change trend. This nonparametric estimator is insensitive to outliers and non-normal distributions. The slope $\beta$ is calculated as:

$$\beta = \text{Median}\left(\frac{x_j - x_i}{j - i}\right), \forall 1 \leq i < j \leq n, \qquad (5)$$

where $x_i$ is the LAI values in year $i$.

A positive $\beta$ indicates an upward trend, and a negative $\beta$ indicates a downward trend.

### 3.2.2 Rescaled range analysis and Hurst exponent

We used rescaled range analysis to calculate the Hurst exponent and the average $V$ statistic, so as to quantify the long-term persistence and future trend continuity of each LAI time series.

For a time series of total length $N$, we divided the series into contiguous sub-series with a given block size $n$. For each sub-series with block size $n$, we calculated the range $R(n)$ and the standard deviation $S(n)$. The expected value of the rescaled range $R(n)/S(n)$ follows a power-law scaling relation with block size $n$:

$$E\left[\frac{R(n)}{S(n)}\right] = C \times n^{H}, \qquad (6)$$

where $C$ is the empirical scaling constant; and $H$ is the Hurst exponent.

We plotted $\lg[R(n)/S(n)]$ against $\lg(n)$ on a double logarithmic axis, and estimated the Hurst exponent $H$ as the slope of the fitted straight line.

To verify the reliability of the Hurst exponent and determine the optimal scaling range, we calculated the $V$ statistic for each block size $n$ as:

$$V(n) = \frac{(R/S)_n}{\sqrt{n}}, \qquad (7)$$

where $V(n)$ is the $V$ statistic for block size $n$; $R$ is the range of cumulative departures within each subseries; and $S$ is the standard deviation of the original subseries values.

We took the mean value of $V$ statistics across all valid block sizes as the average $V$ statistic, which reflects the overall stability of the persistence feature. The classification criteria for persistence types are as follows: $H > 0.5000$ shows persistent characteristics, meaning the historical trend will continue in the future; $H = 0.5000$ presents a random walk state with no significant long-term memory; and $H < 0.5000$ shows anti-persistent characteristics, meaning the historical trend will reverse in the future (Mandelbrot and Wallis, 1969).

### 3.2.3 Pearson correlation analysis

We used the Pearson correlation coefficient to quantify the linear relationship between each LAI metric and annual precipitation at both the whole study area scale and the subregion scale.

For paired time series of LAI and precipitation with length $n$ ($n = 39$ in this study), the Pearson correlation coefficient $r$ is calculated as:

$$r = \frac{\sum_{i=1}^{n}(x_i - \bar{x})(y_i - \bar{y})}{\sqrt{\sum_{i=1}^{n}(x_i - \bar{x})^2}\sqrt{\sum_{i=1}^{n}(y_i - \bar{y})^2}}, \qquad (8)$$

where $y_i$ is the annual precipitation in year $i$ (mm); $\bar{x}$ is the long-term mean LAI over the study period; and $\bar{y}$ is the long-term mean annual precipitation over the study period (mm).

We tested the significance of $r$ with the $t$-test, where the degrees of freedom $df = n - 2$. When $P < 0.05$, the correlation is statistically significant.

#### 3.2.4 Spatial pattern analysis

We calculated the interannual standard deviation of LAI for each grid cell over 1982–2020 to

characterize the intensity of interannual LAI fluctuations. A larger standard deviation indicates stronger interannual variability and lower temporal stability. The standard deviation is computed as:

$$\mathrm{SD} = \sqrt{\frac{1}{n-1}\sum_{i=1}^{n}(\mathrm{LAI}_i - \overline{\mathrm{LAI}})^2}, \qquad (9)$$

where SD stands for the interannual standard deviation of LAI calculated pixel-wise for the period 1982–2020; $n$ is the total number of the study years, $n = 39$ in this study; $\mathrm{LAI}_i$ is the LAI value of the grid cell in year $i$; and $\overline{\mathrm{LAI}}$ is the average LAI value of the grid cell of the whole study period.

We performed Kriging interpolation with topography and climate as auxiliary variables to convert discrete grid indicators into continuous spatial surfaces and partition the basin into high, medium, and low variability zones according to the upstream-midstream-downstream geomorphic gradient. We further applied a 5-a sliding window to calculate the rolling slope and rolling standard deviation of LAI for each pixel. We compared the intensity of LAI variability across the subregions and identified the temporal evolution characteristics of LAI dynamics.

## 4 Results

### 4.1 LAI analysis of the middle and lower reaches of the Irtysh River Basin

**4.1.1 Trend of interannual LAI** We analyzed the interannual variations of three key LAI statistics—annual mean, maximum, and minimum LAI—across the middle and lower reaches of the Irtysh River basin using the Mann-Kendall trend test and Sen' s slope estimates. Figure 2 shows the Mann-Kendall trend test results for LAI in the basin.

**Fig. 2** Mann-Kendall trend test of leaf area index (LAI) for the middle and lower reaches of the Irtysh River Basin. (a), annual mean LAI; (b), annual maximum LAI; (c), annual minimum LAI.

For the annual mean LAI, the Mann-Kendall trend test yielded the $Z$ statistic of 4.8387 and the $P$ value of 0.0000, which is well below the 0.0500 significance level, indicating a significant upward trend. The Sen' s slope was 0.0025/a, indicating that the annual mean LAI increased at approximately 0.0025 per year from 1982 to 2020. This trend reflects the overall improvement in vegetation cover in the basin, closely related to regional climate warming and humidification, including increased precipitation and rising temperatures, as well as the cumulative effects of ecological protection policies. Although there are interannual fluctuations in the series—such as a brief decline during 2010–2015—the long-term upward trend remains stable, suggesting continuous optimization of the "baseline state" of vegetation growth in the basin.

The annual maximum LAI had a $Z$ statistic of 4.2339 and a $P$ value of 0.0000, also passing the significance test and showing a significant upward trend. Its Sen' s slope was 0.0077/a, which is significantly higher than that of the annual mean LAI. The annual maximum LAI mostly corresponded to the optimal growth state of vegetation in the summer growing season. Its substantial increase indicates that the hydrothermal conditions for vegetation growth have been significantly improved, or the peak productivity of communities such as grasslands and forests has been remarkably enhanced, showing a more prominent release of vegetation growth potential.

The annual minimum LAI showed a significant downward trend, with a $Z$ statistic of $-2.9516$ and a $P$ value of 0.0032, which successfully passed the 0.0500 significance test. The Sen' s slope was $-0.0011$/a, indicating that the annual minimum LAI experienced a gradual decrease during the study period. The annual minimum LAI mostly occurred during the winter non-growing season. Its significant decline suggests that environmental constraints or structural changes in vegetation during the non-growing season have intensified, possibly driven by colder winter extremes, shifting snow cover dynamics, or changes in the baseline condition of perennial vegetation. In summary, the annual mean and maximum LAI of the Irtysh River Basin both showed significant upward trends, with the annual maximum LAI exhibiting a higher growth rate, reflecting the simultaneous improvement in overall vegetation condition and the growing-season peak. Conversely, the annual minimum LAI exhibited a significant decreasing trend, indicating a clear divergence in vegetation dynamics between the growing and non-growing seasons.

### 4.1.2 Persistence of interannual variation and persistence of LAI in the Irtysh River Basin

Fig. 3 Rescaled range analysis of LAI in the middle and lower reaches of the Irtysh River Basin.

Figure 1: Fig. 3 Rescaled range analysis of LAI in the middle and lower reaches of the Irtysh River Basin.

To analyze the long-term memory and trend persistence of interannual LAI variations, we performed rescaled range analysis on the 1982–2020 LAI time series, focusing on annual mean, maximum, and minimum LAI. The Hurst exponent $H$ was used to identify persistence (Fig. 3). The Hurst exponent of annual mean LAI was 0.8218, and the lg($V$) fitting slope was 0.3218, indicating strong persistence. This demonstrates that the long-term memory of the average vegetation cover in the basin was stable and influenced by the long growth cycle of extensive grasslands and forests, it was not easily disturbed by short-term extreme climate events. The Hurst exponent of annual maximum LAI was 0.7230, and the lg($V$) fitting slope was 0.2230, also showing strong persistence. Its persistence was slightly lower than that of the annual mean LAI, primarily due to short-term fluctuations caused by extreme climate events during the growing season. However, the overall trend remained dominated by long-term persistence. The Hurst exponent of annual minimum LAI was 0.8011, and the lg($V$) fitting slope was 0.3011, which also confirms strong persistence. Given the significant decreasing trend identified in the Mann-Kendall trend test, this high Hurst value implies that the downward trend of the annual minimum LAI is highly likely to continue in the future, underscoring a persistent long-term decline during the non-growing season.

The Hurst exponents of all indicators were significantly greater than 0.5000 ($P < 0.0100$), and the positive lg($V$) fitting slopes ($V > 0.0000$) further proved that the persistence is real and reliable. The strong persistence of LAI indicates that vegetation dynamics in the basin exhibit clear path dependence, and the historical trends (upward for annual mean and maximum LAI, downward for annual minimum LAI) are likely to continue, providing a scientific basis for ecological protection and long-term planning of the basin.

**Fig. 3** Rescaled range analysis of LAI in the middle and lower reaches of the Irtysh River Basin. (a), annual mean LAI; (b), annual maximum LAI; (c), annual minimum LAI. $H$ denotes the Hurst exponent, which reflects the strength of long-term persistence in the LAI time series; $V$ statistic is a diagnostic metric used to validate the reliability and stability of the Hurst exponent; $R/S$ denotes the rescaled range ratio, in which $R$ represents the range of cumulative deviations from the mean, and $S$ is the sample standard deviation of the time series; and $n$ stands for the sequential block size, namely the length of each contiguous subseries divided from the whole LAI time series during rescaled range analysis.

In summary, the annual mean, maximum, and minimum LAI in the basin all showed strong persistence ($H > 0.7230$), among which the annual mean LAI had the strongest persistence, while the annual maximum LAI had the lowest persistence. These results reveal the response pattern of the vegetation ecosystem to external disturbances and support the prediction of vegetation dynamics.

## 4.2 Trend of LAI for 14 subregions in the middle and lower reaches of the Irtysh River Basin

To comprehensively characterize the spatiotemporal dynamics of LAI, we analyzed three indicators—annual minimum, mean, and maximum LAI—across the 14 subregions in the middle and lower reaches of the Irtysh River from 1982 to 2020. The Mann-Kendall trend test was applied to detect trend significance, while linear regression was used to estimate the rate of change (slope) and evaluate the goodness of fit ($R^2$). The statistical results are illustrated in Figures 4–6, which present the Mann-Kendall trend test results for annual minimum, mean, and maximum LAI, respectively.

### 4.2.1 Trend of annual minimum LAI

The temporal trends of annual minimum LAI displayed pronounced spatial heterogeneity across the 14 subregions from 1982 to 2020, as evidenced by the varying degrees of statistical significance in the Mann-Kendall trend test results. The Mann-Kendall trend test results indicate a divergent pattern characterized by both significant increasing and decreasing tendencies.

Statistically significant increasing trends in annual minimum LAI were observed in nine subregions: Zones 2, 3, 5, 6, 7, 9, 10, 11 and 12 (Fig. 4). These subregions exhibited $P$ values of 0.0012, 0.0084, 0.0006, 0.0446, 0.0018, 0.0013, 0.0072, 0.0111, and 0.0000, respectively, all passing the 0.0500 significance test. The remaining five subregions (Zones 1, 4, 8, 13, and 14) showed no statistically significant trends ($P > 0.0500$), demonstrating high variability with weak explanatory power.

Regarding the magnitude of change, the linear slope of annual minimum LAI was uniformly negative across all zones, varying from $-0.0016$/a in Zone 7 to $-0.0001$/a in Zone 1. The downward trends were most pronounced in Zones 6 and 7, where slopes reached $-0.0011$/a and $-0.0016$/a, respectively. The $R^2$ were generally low, ranging from 0.0097 in Zone 1 to 0.3137 in Zone 12, indicating that while trends existed, the linear relationship for annual minimum LAI was relatively weak in most subregions. These features suggest that annual minimum LAI was strongly influenced by local-scale environmental factors and exhibited limited temporal consistency compared with the annual mean and maximum LAI. The patterns described above were reflected in Figure 4, where the coexistence of increasing and decreasing trends highlight a widespread decline in vegetation cover during the non-growing season under regional environmental constraints.

Fig. 4 Mann-Kendall trend test results for annual minimum LAI values of the 14 subregions in the middle and lower reaches of the Irtysh River Basin from 1982 to 2020.

Figure 2: Fig. 4 Mann-Kendall trend test results for annual minimum LAI values of the 14 subregions in the middle and lower reaches of the Irtysh River Basin from 1982 to 2020.

Fig. 5. Mann-Kendall trend test results for annual mean LAI values of the 14 subregions in the middle and lower reaches of the Irtysh River Basin from 1982 to 2020.

Figure 3: Fig. 5. Mann-Kendall trend test results for annual mean LAI values of the 14 subregions in the middle and lower reaches of the Irtysh River Basin from 1982 to 2020.

### 4.2.2 Trend of annual mean LAI

Annual mean LAI showed a clear and consistent upward trend across most subregions from 1982 to 2020 (Fig. 5), indicating a relatively uniform response at the regional scale. Among the 14 subregions, 9 zones showed statistically significant upward trends, including Zones 1, 4, 6–10, 13, and 14, all with $P$ values below 0.0500. This widespread increase suggests an overall improvement in vegetation conditions during the study period. The remaining 5 subregions, namely Zones 2, 3, 5, 11, and 12, did not exhibit statistically significant trends. Within this group, Zone 3, 11, and 12 approached the significance threshold with a $P$ value of 0.0815, 0.0734, and 0.0625, respectively, whereas Zones 2 and 5 exhibited particularly weak explanatory power, indicating that their variations are relatively unstable.

The magnitude of change further confirmed this pattern, as all slope values were positive and ranged from 0.0004/a in Zone 5 to 0.0047/a in Zone 6, with the most pronounced increase observed in Zone 6. Compared with annual minimum LAI, both the amplitude of change and spatial consistency were markedly higher. The $R^2$ values also showed a clear improvement, reaching up to 0.6440 in Zone 6, with several subregions displaying relatively strong linear

relationships and stable temporal trends. These characteristics are clearly illustrated in Figure 7. Selected to represent diverse environmental gradients, these subregions exhibited coherent upward trends in annual mean LAI, with data points closely aligned with the fitted lines, providing robust evidence for the basin-wide growth.

**Fig. 4** Mann-Kendall trend test results for annual minimum LAI values of the 14 subregions in the middle and lower reaches of the Irtysh River Basin from 1982 to 2020. (a), Zone 1; (b), Zone 2; (c), Zone 3; (d), Zone 4;(e), Zone 5; (f), Zone 6; (g), Zone 7; (h), Zone 8; (i), Zone 9; (j), Zone 10; (k), Zone 11; (l), Zone 12; (m), Zone 13; (n), Zone 14.

Fig. 6. Mann-Kendall trend test results for annual maximum LAI values of the 14 subregions in the middle and lower reaches of the Irtysh River Basin from 1982 to 2020.

Figure 4: Fig. 6. Mann-Kendall trend test results for annual maximum LAI values of the 14 subregions in the middle and lower reaches of the Irtysh River Basin from 1982 to 2020.

**Fig. 5** Mann-Kendall trend test results for annual mean LAI values of the 14 subregions in the middle and lower reaches of the Irtysh River Basin from 1982 to 2020. (a), Zone 1; (b), Zone 2; (c), Zone 3; (d), Zone 4; (e), Zone 5; (f), Zone 6; (g), Zone 7; (h), Zone 8; (i), Zone 9; (j), Zone 10; (k), Zone 11; (l), Zone 12; (m), Zone 13; (n), Zone 14.

### 4.2.3 Trend of annual maximum LAI

Annual maximum LAI exhibited the most pronounced and consistent increasing trends among the

**Fig. 6** Mann-Kendall trend test results for annual maximum LAI values of the 14 subregions in the middle and lower reaches of the Irtysh River Basin from 1982 to 2020. (a), Zone 1; (b), Zone 2; (c), Zone 3; (d), Zone 4; (e), Zone 5; (f), Zone 6; (g), Zone 7; (h), Zone 8; (i), Zone 9; (j), Zone 10; (k), Zone 11; (l), Zone 12; (m), Zone 13; (n), Zone 14.

three indicators, reflecting the strongest vegetation growth signal. A total of 11 subregions showed statistically significant increases, including Zones 1–4, 6–10, 12, and 13, all with $P$ values below 0.0500 (Fig. 6). Only three subregions, namely Zones 5, 11, and 14, did not show statistically significant trends ($P >$ 0.0500), and no decreasing patterns were observed. This distribution highlighted the strong spatial coherence of annual maximum LAI and its dominant upward

tendency. The most pronounced increases occurred in Zones 6, 7, 9, and 10 (slopes of 0.0182/a, 0.0160/a, 0.0146/a, and 0.0207/a, respectively), indicating rapid enhancement in peak vegetation conditions. The $R^2$ were also relatively high across most subregions, peaking at 0.6323 in Zone 6, with several areas exhibiting strong linear relationships and stable temporal dynamics. Figure 8 further illustrates the variation of annual maximum LAI. The significant positive slopes indicate a robust growth trend in peak vegetation productivity, regardless of whether the areas are high-altitude headwaters or lowland plains.

## 4.3 Persistence characteristics of LAI for 14 subregions in the middle and lower reaches of the Irtysh River Basin

To investigate the temporal persistence of LAI dynamics, we applied rescaled range analysis to the annual minimum, mean, and maximum LAI across the 14 subregions in the middle and lower reaches of the Irtysh River Basin from

1982 to 2020. The persistence of each time series was quantified using the Hurst exponent $H$ together with the corresponding $V$ statistic, allowing for an integrated assessment of long-term memory effects.

Overall, the analysis revealed distinct persistence characteristics among the three LAI indicators and across different subregions, indicating varying degrees of temporal continuity in vegetation dynamics (Figs. 7–9). The high values of Hurst observed across the majority of the basin confirm that the vegetation growth trends detected by the Mann-Kendall trend test are likely to persist in the future. These persistence characteristics provide a scientific basis for predicting the long-term response of the Irtysh River Basin' s ecosystem to ongoing environmental changes.

#### 4.3.1 Persistence of annual minimum LAI

Annual minimum LAI exhibited consistent persistence across all 14 subregions in the middle and lower reaches of the Irtysh River Basin, as indicated by Hurst values that were uniformly greater than 0.5000 (Fig. 7). This suggests that the temporal evolution of annual minimum LAI was dominated by long-term memory effects, implying that past trends were likely to continue. The Hurst exponent for annual minimum LAI ranged from 0.7049 to 0.8504 across the study area.

When examining the ecological partitions, the central steppe-riparian transition group exhibited the strongest average persistence ($H = 0.7933$), with Zone 7 displaying the highest individual value ($H = 0.8504$), suggesting strong temporal continuity in riparian environments during the non-growing season. The lowland forest-wetland group also demonstrated robust continuity with an average Hurst exponent of 0.7898. In contrast, the mountainous and piedmont steppe group showed comparatively weaker persistence on average ($H = 0.7483$), and the lowest overall Hurst value was observed in Zone 3 ($H = 0.7049$). The average $V$ statistic showed a similar spatial pattern, further confirming the robustness of the persistence signals. These results indicate that although annual minimum LAI exhibited complex spatial variability in the direction of its trend, its temporal behavior remains consistently governed by persistent dynamics, especially in the central transition and downstream lowland ecosystems.

#### 4.3.2 Persistence of annual mean LAI

Annual mean LAI showed the strongest and consistent persistence across all subregions (Fig. 8), with Hurst exponent values generally higher than those of both annual minimum and maximum LAI. This indicates a highly stable temporal structure with robust long-term memory in average vegetation conditions. The Hurst exponent for annual mean LAI was concentrated in a very high range, between 0.8274 and 0.9345.

Across the three groups, annual mean LAI persistence remained remarkably stable and uniform: the central steppe-riparian transition group (average $H =$

Fig. 7. Rescaled range analysis results for annual minimum LAI values of the 14 subregions in the middle and lower reaches of the Irtysh River Basin from 1982 to 2020.

Figure 5: Fig. 7. Rescaled range analysis results for annual minimum LAI values of the 14 subregions in the middle and lower reaches of the Irtysh River Basin from 1982 to 2020.

Fig. 8

Figure 6: Fig. 8

0.8868), the lowland forest-wetland group (average $H = 0.8822$), and the mountainous and piedmont steppe group (average $H = 0.8811$). Notably, Zones 7 ($H = 0.9345$) and 5 ($H = 0.9153$) within the central transition group exhibited the highest values, indicating highly stable temporal evolution in these meadow and riparian communities. The lowest value, though still indicating very strong persistence, was found in Zone 8 ($H = 0.8274$) in the lowland forest-wetland group. The consistently high Hurst

values and corresponding $V$ statistics suggest that the widely observed upward trends in annual mean LAI are highly likely to persist, reinforcing its reliability as an indicator of long-term vegetation dynamics across all geomorphic gradients.

**Fig. 7** Rescaled range analysis results for annual minimum LAI values of the 14 subregions in the middle and lower reaches of the Irtysh River Basin from 1982 to 2020. (a), Zone 1; (b), Zone 2; (c), Zone 3; (d), Zone 4; (e), Zone 5; (f), Zone 6; (g), Zone 7; (h), Zone 8; (i), Zone 9; (j), Zone 10; (k), Zone 11; (l), Zone 12; (m), Zone 13; (n), Zone 14.

**Fig. 8** Rescaled range analysis results for annual mean LAI values of the 14 subregions in the middle and lower reaches of the Irtysh River Basin from 1982 to 2020. (a), Zone 1; (b), Zone 2; (c), Zone 3; (d), Zone 4; (e), Zone 5; (f), Zone 6; (g), Zone 7; (h), Zone 8; (i), Zone 9; (j), Zone 10; (k), Zone 11; (l), Zone 12; (m), Zone 13; (n), Zone 14.

### 4.3.3 Persistence of annual maximum LAI

Annual maximum LAI exhibited consistent persistence across the study area (Fig. 9), indicating

**Fig. 9** Rescaled range analysis of annual maximum LAI values of the 14 subregions in the middle and lower reaches of the Irtysh River Basin from 1982 to

Fig. 9

Figure 7: Fig. 9

2020. (a), Zone 1; (b), Zone 2; (c), Zone 3; (d), Zone 4; (e), Zone 5; (f), Zone 6; (g), Zone 7; (h), Zone 8; (i), Zone 9; (j), Zone 10; (k), Zone 11; (l), Zone 12; (m), Zone 13; (n), Zone 14.

that peak vegetation productivity—which reflects favorable hydrothermal conditions during the growing season—was governed by a persistent temporal structure. The Hurst exponent for annual maximum LAI varied between 0.7027 and 0.9264.

Significant differences in persistence were observed among the groups. The lowland forest-wetland group displayed the highest average persistence ($H$=0.8561), with Zone 2 demonstrating particularly strong long-term memory ($H$=0.9264). This suggests that peak vegetation growth in the semi-humid downstream temperate forests and peatlands is highly stable and path-dependent. The mountainous and piedmont steppe group also exhibited strong persistence, averaging 0.8279. Conversely, the central steppe-riparian transition group showed the lowest average persistence ($H$=0.7898), with Zones 11 displaying the weakest temporal continuity ($H$=0.7027). This implies that peak productivity in the hydro-climatic transition zone may be more sensitive to interannual fluctuations in precipitation and seasonal flooding. The average $V$ statistic values remained consistently positive, reinforcing the reliability of these results.

## 4.4 Correlation between LAI and annual precipitation

### 4.4.1 Correlation between annual maximum LAI and annual precipitation

Across the middle and lower reaches of the Irtysh River Basin, annual maximum LAI showed an overall positive response to annual precipitation, although the strength of the relationship varied among subregions. Significant positive correlations were observed in 9 of the 14 subregions, including Zones 1–5, 7, 11, 12, and 14, with correlation coefficients ranging from 0.3313 to 0.6025 ($P$<0.0500) as shown in Table 1. These results indicate that precipitation was an important factor controlling peak vegetation growth in most subregions. The strongest precipitation responses were observed in Zones 3, 5, 12, and 14, with correlation coefficients of 0.5307, 0.6025, 0.5805, and 0.5574, respectively ($P$<0.0010). These subregions collectively encompass diverse habitats, including central steppe-riparian transition areas, downstream lowland ecosystems, and mountainous and piedmont steppe communities. In these subregions, vegetation growth is strongly associated with water availability; precipitation variability directly affects soil moisture conditions and vegetation productivity. The relatively abundant precipitation and river-supported moisture conditions provide favorable environments for meadow, steppe, and riparian vegetation development, allowing vegetation canopy expansion to respond effectively to interannual precipitation variations. Furthermore, the interaction between precipitation inputs and riverine hydrological processes may enhance vegetation responses by alleviating seasonal water stress. Weaker, yet significant, and positive responses were also observed in Zones 1, 2, 4, 7, and 11, further confirming the widespread dependence of maximum LAI on precipitation.

**Table 1** Pearson correlation analysis results between annual maximum leaf area index (LAI) and annual precipitation across subregions

| Zone | Correlation coefficient | *P*-Value | Correlation relationship |
|---:|---:|---:|---|
| 1 | 0.4820 | 0.0019 | Weak positive (significant) |
| 2 | 0.4869 | 0.0017 | Weak positive (significant) |
| 3 | 0.5307 | 0.0005 | Moderate positive (significant) |
| 4 | 0.4014 | 0.0113 | Weak positive (significant) |
| 5 | 0.6025 | 0.0000 | Moderate positive (significant) |
| 6 | 0.2517 | 0.1221 | Very weak positive (not significant) |
| 7 | 0.3313 | 0.0394 | Weak positive (significant) |
| 8 | 0.0642 | 0.6977 | Very weak positive (not significant) |
| 9 | 0.2304 | 0.1582 | Very weak positive (not significant) |
| 10 | 0.3083 | 0.0562 | Weak positive (not significant) |
| 11 | 0.4526 | 0.0038 | Weak positive (significant) |
| 12 | 0.5805 | 0.0001 | Moderate positive (significant) |
| 13 | −0.1884 | 0.2507 | Very weak negative (not significant) |
| 14 | 0.5574 | 0.0002 | Moderate positive (significant) |

Note: Significant indicates $P$<0.0500.

In contrast, weaker or non-significant correlations were observed in Zones 6, 8–10, and 13. The correlation coefficients in these subregions ranged from −0.1884 to 0.2517, indicating a limited response of peak vegetation growth to precipitation variability. Zone 13 showed a weak negative correlation ($r$= −0.1884, $P$=0.2507), suggesting that vegetation growth in the alpine transition region was not primarily controlled by annual precipitation. Instead, elevation-related temperature limitation, complex terrain conditions, and snowmelt-dominated hydrological processes may impose stronger constraints on vegetation development.

Overall, annual maximum LAI exhibited a widespread positive relationship with annual precipitation, demonstrating that water availability was a major limiting factor for peak vegetation growth across most subregions of the study area.

#### 4.4.2 Correlation between annual mean LAI and annual precipitation

Across the middle and lower reaches of the Irtysh River Basin, annual mean LAI showed a generally stronger and more consistent response to annual precipitation compared with annual maximum LAI. Significant positive correlations were detected in 8 subregions, including Zones 1–5, 11, 12, and 14, with correlation coefficients ranging from 0.4541 to 0.6626 ($P$<0.0500). The highest correlation occurred in Zone 12 ($r$=0.6626), followed by Zone 5 ($r$=0.5835) and Zone 3 ($r$=0.5728) as shown in Table 2.

**Table 2** Pearson correlation analysis between annual mean LAI and annual precipitation across subregions

| Zone | Correlation coefficient | $P$-value | Correlation relationship |
|---:|---:|---:|---|
| 1 | 0.4710 | 0.0025 | Weak positive (significant) |
| 2 | 0.5020 | 0.0011 | Moderate positive (significant) |
| 3 | 0.5728 | 0.0001 | Moderate positive (significant) |
| 4 | 0.4541 | 0.0037 | Weak positive (significant) |
| 5 | 0.5835 | 0.0001 | Moderate positive (significant) |
| 6 | 0.0707 | 0.6687 | Very weak positive (not significant) |

| Zone | Correlation coefficient | $P$-value | Correlation relationship |
|---|---|---|---|
| 7 | 0.1181 | 0.4738 | Very weak positive (not significant) |
| 8 | −0.0101 | 0.9516 | Very weak negative (not significant) |
| 9 | 0.0211 | 0.8987 | Very weak positive (not significant) |
| 10 | 0.0800 | 0.6297 | Very weak positive (not significant) |
| 11 | 0.5269 | 0.0006 | Moderate positive (significant) |
| 12 | 0.6626 | 0.0000 | Moderate positive (significant) |
| 13 | −0.2180 | 0.1824 | Very weak negative (not significant) |
| 14 | 0.5381 | 0.0004 | Moderate positive (significant) |

Note: Significant indicates $P<0.0500$.

The stronger relationship between annual mean LAI and precipitation suggests that precipitation influences not only peak vegetation conditions but also the overall annual vegetation productivity. The subregions with significant positive correlations (Zones 1-5, 11, 12, and 14) collectively encompass steppe, meadow, and riparian ecosystems, where vegetation growth is closely linked with seasonal water availability. In these areas, precipitation variations can regulate soil moisture conditions and influence vegetation development throughout the growing season, resulting in a more integrated response reflected by annual mean LAI.

Compared with annual maximum LAI, annual mean LAI showed higher correlation coefficients in several subregions, indicating greater sensitivity to long-term precipitation variability. For example, Zone 12 exhibited a stronger correlation for annual mean LAI ($r$=0.6626) than for annual maximum LAI ($r$=0.5805). This difference suggests that annual mean LAI captures cumulative vegetation responses to precipitation fluctuations more effectively than annual maximum LAI, which mainly reflects short-term peak growth conditions.

However, weak or non-significant correlations were observed in Zones 6–10 and 13. These areas include downstream forest–wetland ecosystems and high-altitude transition zones, where vegetation growth may be buffered by stable groundwater conditions, wetland water storage, or

environmental limitations. Consequently, annual precipitation alone may not fully determine vegetation dynamics in these ecosystems.

Overall, annual mean LAI exhibited the strongest and most stable response to precipitation variability, highlighting the dominant role of water availability in regulating overall vegetation conditions across the study area.

### 4.4.3 Correlation between annual minimum LAI and annual precipitation

In contrast to annual maximum and mean LAI, annual minimum LAI showed weak and generally insignificant relationships with annual precipitation across the study area. None of the 14 subregions exhibited statistically significant correlations, with correlation coefficients ranging from −0.3121 to 0.1183 ($P > 0.0500$) as shown in Table 3.

**Table 3** Pearson correlation analysis between annual minimum LAI and annual precipitation across subregions

| Zone | Correlation coefficient | $P$-value of annual minimum LAI | Correlation relationship |
|---|---|---|---|
| 1 | −0.0682 | 0.6801 | Very weak negative (not significant) |
| 2 | −0.1202 | 0.4661 | Very weak negative (not significant) |
| 3 | −0.1055 | 0.5225 | Very weak negative (not significant) |
| 4 | −0.2054 | 0.2098 | Very weak negative (not significant) |
| 5 | −0.1024 | 0.5349 | Very weak negative (not significant) |
| 6 | −0.2052 | 0.2101 | Very weak negative (not significant) |
| 7 | −0.1526 | 0.3536 | Very weak negative (not significant) |

| Zone | Correlation coefficient | $P$-value of annual minimum LAI | Correlation relationship |
|---|---|---|---|
| 8 | −0.1095 | 0.5068 | Very weak negative (not significant) |
| 9 | −0.3121 | 0.0531 | Weak negative (not significant) |
| 10 | −0.2303 | 0.1584 | Very weak negative (not significant) |
| 11 | 0.1183 | 0.4732 | Very weak positive (not significant) |
| 12 | −0.2137 | 0.1915 | Very weak negative (not significant) |
| 13 | −0.2206 | 0.1772 | Very weak negative (not significant) |
| 14 | 0.0398 | 0.8101 | Very weak positive (not significant) |

Note: Significant indicates $P < 0.0500$.

Most subregions showed weak negative correlations between annual minimum LAI and precipitation. For example, Zones 9 and 12 exhibited correlation coefficients of −0.3121 and −0.2137, respectively, although these relationships did not reach statistical significance. The weak negative responses suggest that increased precipitation does not necessarily enhance vegetation conditions during periods of minimum growth, particularly when vegetation activity is limited by seasonal dormancy or other environmental constraints.

Several subregions showed weak positive relationships, such as Zone 11 ($r = 0.1183$), but the correlations remained insignificant. This indicates that even in regions with relatively favorable hydrothermal conditions, precipitation has limited influence on minimum vegetation states. In downstream forest–wetland ecosystems, stable groundwater availability and floodplain storage capacity may reduce vegetation dependence on annual precipitation fluctuations. Similarly, alpine regions are more strongly affected by temperature limitation and seasonal snow processes.

The contrasting responses between annual minimum LAI and the other two LAI indicators demonstrate that vegetation sensitivity to precipitation is highly dependent on growth stage. During dormant or low-productivity periods, vegetation activity is mainly restricted by physiological processes and environmental constraints rather than annual precipitation variability. Therefore, annual minimum LAI appears to be a less effective indicator for detecting precipitation-driven vegetation changes in the Irtysh River Basin.

### 4.4.4 Synthesis of LAI-precipitation relationships

The relationships between annual precipitation and different LAI indicators revealed clear differences in vegetation sensitivity across the middle and lower reaches of the Irtysh River Basin. Annual maximum LAI and LAI showed widespread positive correlations with

precipitation, whereas annual minimum LAI exhibited weak and insignificant responses. Significant positive correlations occurred in 64.29% of subregions for annual maximum LAI and 57.14% for annual mean LAI, demonstrating the dominant role of precipitation in regulating vegetation growth during active periods.

Spatially, precipitation sensitivity was strongest in the central steppe-riparian transition regions and piedmont areas, particularly Zones 5 and 12, where both annual maximum LAI and LAI showed strong positive correlations. These subregions combine relatively favorable water conditions with vegetation communities that are highly responsive to moisture availability. In contrast, alpine transition areas and stable downstream wetland ecosystems showed weaker precipitation responses because vegetation dynamics were buffered by temperature constraints, groundwater availability, or ecosystem stability.

The three LAI indicators reflected different aspects of vegetation responses to precipitation. Annual maximum LAI was sensitive to precipitation-induced changes in peak canopy development, while annual mean LAI integrated seasonal vegetation responses and showed a more stable relationship with precipitation. In contrast, annual minimum LAI was largely independent of precipitation variability, indicating that low-productivity vegetation states were controlled mainly by ecological constraints and seasonal processes.

Overall, precipitation was a key driver of vegetation growth dynamics in the Irtysh River Basin, particularly during periods of active vegetation development. However, the spatial heterogeneity of precipitation–LAI relationships highlights the importance of considering regional hydro-ecological conditions when evaluating vegetation responses to climate variability.

## 4.5 Spatial pattern analysis of LAI

We conducted a 5-year rolling window analysis, the spatial patterns of LAI trend and interannual variability exhibited substantial temporal evolution across the Irtysh River Basin during 1982–2020 (Figs. 10 and 11). The rolling slope was used to characterize the direction and magnitude of vegetation change, whereas the rolling standard deviation was employed to quantify interannual variability.

The spatial distribution of rolling LAI trends showed substantial temporal heterogeneity throughout the study period (Fig. 10). During 1982–2001, rolling slope values ranged from −0.1109 to 0.0994. Positive trends dominated most regions, particularly along the central river corridors and northern lowland areas, whereas negative trends were mainly distributed in the southeastern mountainous and piedmont regions. During 2002–2006, the spatial pattern became increasingly fragmented, with positive and negative trends occurring simultaneously across different ecological zones. During 2007–2020, the magnitude of LAI variation increased markedly, with rolling slope values ranging from −0.3608 to 0.2889. Positive trends remained concentrated in parts of the central and downstream regions, whereas negative trends expanded mainly across the southeastern dry regions and parts of the southwestern steppe areas.

The rolling standard deviation revealed an increasing tendency of interannual LAI variability over the study period (Fig. 11). During the early period (1982–2001), vegetation dynamics were relatively stable, with most areas exhibiting standard deviation values below 0.0800 and an overall range of 0.0015–0.2886. After 2002, regions with high variability gradually expanded, indicating enhanced fluctuations in vegetation conditions. During 2007–2020, the variability range expanded to 0.0008–0.4620, indicating stronger interannual instability compared with the earlier period.

Pronounced spatial differences in LAI variability were observed among ecological zones. Higher variability was mainly distributed in the southeastern mountainous and piedmont steppe regions (Zones 3, 4, 9, 12, and 13), where vegetation growth is strongly constrained by limited precipitation and climatic fluctuations. Several transitional agricultural and riparian regions (Zones 5, 7, 10, and 11) also exhibited moderate-to-high variability, reflecting the combined influence of precipitation variability, irrigation activities, and hydrological regulation. In contrast, the downstream forest–wetland regions (Zones 1, 2, 6, 8, and 14) generally showed lower variability because abundant moisture availability and strong hydrological connectivity buffered

vegetation against short-term climatic fluctuations. However, these regions also experienced increased variability after 2007, indicating enhanced sensitivity of vegetation dynamics to environmental change. Overall, the rolling-window analysis demonstrated that vegetation dynamics in the middle and lower reaches of Irtysh River became increasingly heterogeneous after the early 2000s. Although vegetation improvement remained widespread in humid downstream and river-associated regions, vegetation fluctuations intensified particularly in water-limited southeastern areas, highlighting the divergent responses of different ecological zones to climate variability and hydrological changes.

**Fig. 10** Spatial patterns of rolling trend slopes of LAI over multi-period 5-year sliding windows in the middle and lower reaches of the Irtysh River Basin. (a), 1982–1986; (b), 1987–1991; (c), 1992–1996; (d), 1997–2001; (e), 2002–2006; (f), 2007–2011; (g), 2012–2016; (h), 2017–2020.

Spatial patterns of rolling trend slopes of LAI over multi-period 5-year sliding windows in the middle and lower reaches of the Irtysh River Basin.

Figure 8: Spatial patterns of rolling trend slopes of LAI over multi-period 5-year sliding windows in the middle and lower reaches of the Irtysh River Basin.

Fig. 11 Spatial differentiation of annual LAI interannual variability across the middle and lower reaches of the Irtysh River Basin under multi-period 5-year sliding window segmentation. Panels: (a) 1982-1986; (b) 1987-1991; (c) 1992-1996; (d) 1997-2001; (e) 2002-2006; (f) 2007-2011; (g) 2012-2016; (h) 2017-2020. Legend: boundary of the study area, Irtysh River, tributary. Color scale: annual LAI variability, 0.0-0.5.

Figure 9: Fig. 11 Spatial differentiation of annual LAI interannual variability across the middle and lower reaches of the Irtysh River Basin under multi-period 5-year sliding window segmentation. Panels: (a) 1982-1986; (b) 1987-1991; (c) 1992-1996; (d) 1997-2001; (e) 2002-2006; (f) 2007-2011; (g) 2012-2016; (h) 2017-2020. Legend: boundary of the study area, Irtysh River, tributary. Color scale: annual LAI variability, 0.0-0.5.

## 5 Discussion

The spatial heterogeneity of LAI dynamics in the middle and lower reaches of the Irtysh River reflects the combined effects of hydroclimatic gradients, ecosystem structure, and anthropogenic regulation. The study area spans a pronounced transition from dry mountainous and piedmont

**Fig. 11** Spatial differentiation of annual LAI interannual variability across the middle and lower reaches of the Irtysh River Basin under multi-period 5-year sliding window segmentation. (a), 1982-1986; (b), 1987-1991; (c), 1992-1996; (d), 1997-2001; (e), 2002-2006; (f), 2007-2011; (g), 2012-2016; (h), 2017-2020.

ecosystems in the southeast to humid forest-wetland ecosystems in the downstream lowlands, resulting in distinct vegetation responses to environmental variability (Yin et al., 2017).

The mountainous and piedmont steppe zone (Zones 3, 4, 9, 12, and 13) have relatively strong LAI fluctuations and frequent negative trends during some periods. These regions are characterized by low precipitation, complex terrain, and water-limited vegetation systems, where vegetation growth is highly sensitive to interannual variations in precipitation and soil moisture availability. Similar water constraints have been widely reported in Central Asian drylands, where vegetation productivity is primarily regulated by moisture supply (Zhang et al., 2021; Li et al., 2023).

The central steppe-riparian transition zone (Zones 5, 7, 10, and 11) showed intermediate LAI variability and complex spatial patterns. This region represents an ecological transition between semi-arid grasslands and humid downstream ecosystems, where vegetation dynamics are jointly controlled by precipitation variability, river hydrological processes, groundwater availability, and agricultural activities. The coexistence of grassland, meadow, riparian vegetation, and cropland increases ecosystem sensitivity to changes in water availability (Li et al., 2024b).

The lowland forest–wetland zone (Zones 1, 2, 6, 8, and 14) generally exhibited relatively stable

vegetation dynamics and lower interannual variability. Higher precipitation, extensive wetlands, and strong hydrological connectivity provide additional water buffering capacity, reducing the direct dependence of vegetation growth on short-term precipitation fluctuations (Liu et al., 2022; Li et al., 2024b). However, the increasing variability observed after 2007 suggests that even moisture-rich ecosystems may become increasingly sensitive to climatic fluctuations under ongoing environmental changes.

The contrasting responses of annual minimum, mean, and maximum LAI indicate different ecological controls on vegetation dynamics. Annual maximum LAI showed the strongest increasing trend, suggesting that favorable growing-season conditions primarily promoted canopy expansion and vegetation productivity. Annual mean LAI exhibited relatively persistent increasing patterns, reflecting the cumulative effects of long-term environmental improvement and ecosystem recovery (Yue et al., 2002).

In contrast, annual minimum LAI displayed weaker and more spatially heterogeneous responses, indicating stronger regulation by local environmental conditions. During unfavorable growth periods, vegetation conditions are more strongly influenced by soil moisture availability, groundwater conditions, and seasonal water stress rather than by annual climatic averages alone. Previous studies have demonstrated that vegetation responses to drought often involve cumulative and lagged effects, particularly in water-limited ecosystems (Li et al., 2023). Soil moisture can further regulate the timing and intensity of vegetation responses by buffering short-term precipitation variability (Zhang et al., 2021).

The relatively weak response of annual minimum LAI in downstream forest-wetland regions may result from their stronger hydrological buffering capacity, whereas stronger fluctuations in mountainous and piedmont steppe regions indicate greater sensitivity to water availability. These differences highlight the importance of ecosystem-specific controls on vegetation response.

The observed LAI increase in the middle and lower reaches of the Irtysh River is consistent with previous studies reporting widespread vegetation greening in Central Asia during recent decades (Piao et al., 2011; Yin et al., 2017). However, this study further demonstrates that greening trends were spatially heterogeneous, with different ecological zones exhibiting contrasting responses due to differences in water availability, vegetation composition, and hydrological conditions.

Previous studies have identified precipitation as a dominant factor controlling vegetation dynamics in Central Asian drylands (Yin et al., 2017; Li et al., 2023). Our results support this conclusion but also highlight the importance of hydrological connectivity in regulating vegetation responses, particularly in riparian and wetland ecosystems. Similar nonlinear relationships between vegetation productivity and water availability have been observed globally, where vegetation gradually shifts from water limitation toward weaker precipitation dependence under humid conditions (Nemani et al., 2003). The persistent characteristics of LAI dynamics observed in this study are also consistent with long-term memory effects in vegetation systems, indicating that previous environmental conditions may influence subsequent vegetation states (Yue et al., 2002).

The observed increase in LAI was primarily associated with favorable climatic conditions, whereas human activities likely contributed to regional differences. Increasing precipitation and warming temperatures may have promoted vegetation recovery by enhancing water availability and extending the growing season, consistent with the global dryland greening phenomenon (Piao et al., 2011; Yin et al., 2017).

However, vegetation responses differed among ecological zones. In the mountainous and piedmont steppe zone (Zones 3, 4, 9, 12, and 13), vegetation dynamics remained strongly constrained by precipitation availability. In contrast, vegetation changes in the central steppe–riparian transition zone (Zones 5, 7, 10, and 11) were additionally influenced by irrigation activities and river regulation. Reservoir operations and agricultural water use can modify local water availability and consequently affect vegetation growth patterns (Xia et al., 2022; Li et al., 2024b).

Although human activities may explain part of the spatial variability in LAI trends, direct quantitative assessment was limited by the lack of long-term anthropogenic datasets. Future studies incorporating irrigation intensity, land-use change, and water management information are

needed to separate climatic and human contributions.

Besides precipitation, temperature and solar radiation also regulate LAI dynamics through their effects on vegetation phenology, photosynthesis, and water balance. Temperature influences growing-season length, photosynthetic activity, and snowmelt timing, which are particularly important in high-latitude and mountainous regions (Buermann et al., 2014; Li et al., 2023).

However, warming effects are spatially dependent. In humid downstream forest-wetland regions (Zones 1, 2, 6, 8, and 14), increased temperature may extend the growing season and promote vegetation productivity. In contrast, in dry mountainous and piedmont steppe regions (Zones 3, 4, 9, 12, and 13), warming may enhance evapotranspiration and increase water stress, thereby limiting vegetation growth (Li et al., 2024b).

Solar radiation provides essential energy for photosynthesis and canopy development. Adequate radiation can enhance carbon assimilation, particularly in humid regions where water availability is sufficient. However, excessive radiation combined with drought conditions may increase atmospheric demand and intensify vegetation stress in arid environments.

Overall, vegetation dynamics in the middle and lower reaches of the Irtysh River are controlled by the interaction of precipitation, temperature, radiation, and hydrological processes. Water availability remains the dominant limiting factor in dry mountainous and steppe ecosystems, whereas temperature and radiation become increasingly important in humid downstream forests and wetlands. These interactions explain the strong spatial heterogeneity of LAI trends and persistence across different ecological zones.

## 6 Conclusions

This study investigated the long-term variations, spatial heterogeneity, and future persistence of LAI across the middle and lower reaches of the Irtysh River Basin from 1982 to 2020. The results demonstrated significant increases in annual mean LAI and maximum, with Sen' s slopes of 0.0025/a and 0.0077/a, respectively, whereas annual minimum LAI showed a significant decreasing trend with a slope of $-0.0011$/a, revealing divergent trajectories among different vegetation states. Spatial analyses indicated substantial heterogeneity in LAI dynamics among mountainous and piedmont regions, steppe–riparian transition zones, and downstream forest–wetland landscapes, reflecting the influence of contrasting environmental conditions and ecosystem characteristics. Rolling-window analysis further revealed enhanced spatial divergence and increased interannual variability after the early 2000s, suggesting a transition toward more heterogeneous vegetation dynamics across the study area. Rescaled range analysis showed strong persistence in all LAI indicators, with Hurst exponents consistently exceeding 0.7000, indicating that the observed vegetation trajectories are likely to persist under future environmental conditions. Correlation analysis demonstrated that precipitation was an important factor influencing annual mean and maximum LAI variations in many subregions, while annual minimum LAI exhibited weak responses to precipitation variability, suggesting different sensitivities among vegetation states. These findings improve the understanding of vegetation dynamics and future ecological stability in transboundary arid and semi-arid river basins and provide scientific support for ecosystem management under changing environmental conditions.

## Conflict of interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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## Author contributions

Conceptualization: KUANG Jingchao, LIU Dengfeng; Data curation: KUANG Jingchao, LIU Dengfeng; Methodology: KUANG Jingchao, LIU Dengfeng; Formal analysis: KUANG Jingchao, LIU Dengfeng; Writing - original draft preparation: KUANG Jingchao, LIU Dengfeng; Writing - review and editing: KUANG Jingchao, LIU Dengfeng, MA Chuanhui, MING Bo, YANG Yuanyuan, MING Guanghui, LI Mingliang, Mohd Yawar Ali KHAN, Fiaz HUSSAIN, MENG Xianmeng, LI Qiang; Funding acquisition: LIU Dengfeng, LI Mingliang; Supervision: LIU Dengfeng. All authors approved the manuscript.

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