Scientific Journal of Technology Volume 8 Issue 3, 2026
ISSN: 2688-8645

Temporal Retrieval of LAI in the Wuding River Basin Based on a Hybrid Radiative Transfer Model (2001–2024)

Zhengze Ma

School of Surveying and Land Information Engineering, Henan Polytechnic University, Jiaozuo Henan, 454000, China

Abstract

Leaf Area Index (LAI) is a key biophysical indicator characterizing vegetation canopy structure and ecosystem productivity. Focusing on the complex terrain of the Wuding River Basin in the Loess Plateau, this study performed LAI retrieval using remote sensing data from 2001 to 2024 combined with advanced algorithms.Based on the analysis of long-term time-series LAI data, this study revealed that LAI in the Wuding River Basin exhibited a distinct unimodal monthly growth rhythm: the peak value steadily occurred in July and August, the midsummer period with the most abundant hydrothermal conditions, while the trough value appeared in January and February during the vegetation dormancy stage.The results demonstrated that driven by the long-term implementation of ecological restoration projects, the vegetation canopy structure in the basin has been significantly improved, and the intra-annual fluctuation amplitude of LAI showed an expanding trend year by year, which accurately reflects the dynamic enhancement of radiative energy absorption capacity and transpiration intensity during the vegetation growing season.

Keywords

Leaf Area Index; Hybrid Radiative Transfer Model; Time-series Retrieval.

1. Introduction

Leaf Area Index (LAI) is a key biophysical parameter that characterizes vegetation canopy structure and reflects vegetation growth status. It is defined as the total one-sided area of all plant leaves per unit ground surface area[4]. LAI is directly related to vegetation photosynthetic efficiency, transpiration intensity, and nutrient cycling rate. It also serves as a critical input variable for simulating eco-hydrological processes, estimating terrestrial carbon cycles, and evaluating regional soil and water conservation effects. As explicitly designated by the Global Climate Observing System (GCOS), LAI is one of the Essential Climate Variables (ECVs) and acts as an important bridge for material and energy exchange between surface vegetation and the atmosphere. Accurately obtaining the spatiotemporal dynamics of LAI at the regional scale can not only quantify vegetation productivity and evaluate the effectiveness of ecological restoration projects, but also provide essential data support for simulating water and sediment transport and assessing ecosystem health. It plays an irreplaceable role in understanding the response mechanisms of terrestrial ecosystems to global climate change.

The Wuding River Basin is located in the transition zone between the northern Loess Plateau and the southern Mu Us Sandy Land, with a total watershed area of approximately 30,200 km^2. As one of the major tributaries in the middle reaches of the Yellow River, it is also one of the main sediment source areas entering the Yellow River[5]. The basin features an interlaced distribution of loess hilly-gully landscapes and aeolian sand landscapes. The loose soil texture, uneven and concentrated precipitation result in an extremely fragile ecological environment and serious soil erosion. Vegetation coverage exhibits strong spatial heterogeneity: from forest and shrub vegetation in the southern part, to grassland in the central part, and to desert shrubs in the northern part, showing a distinct gradient change in vegetation types.

As a key implementation area for ecological protection and restoration projects on the Loess Plateau and a critical node for the high-quality development strategy of the Yellow River Basin, the basin has long promoted a series of ecological restoration projects, including the Grain for Green Project, sand prevention and control, and comprehensive small watershed management. Affected by project implementation, climate fluctuations, human activities and other factors, vegetation coverage and canopy structure in the basin have shown significant interannual variations and seasonal fluctuations. Long-term, continuous, and high-precision time-series LAI data serve as the fundamental prerequisite for scientifically evaluating the effects of ecological restoration, revealing the coupling mechanism between vegetation growth and water-sediment transport, and supporting decision-making for ecological protection and integrated watershed management. They also represent the core data requirement for solving the difficult problems of regional ecological environment governance.

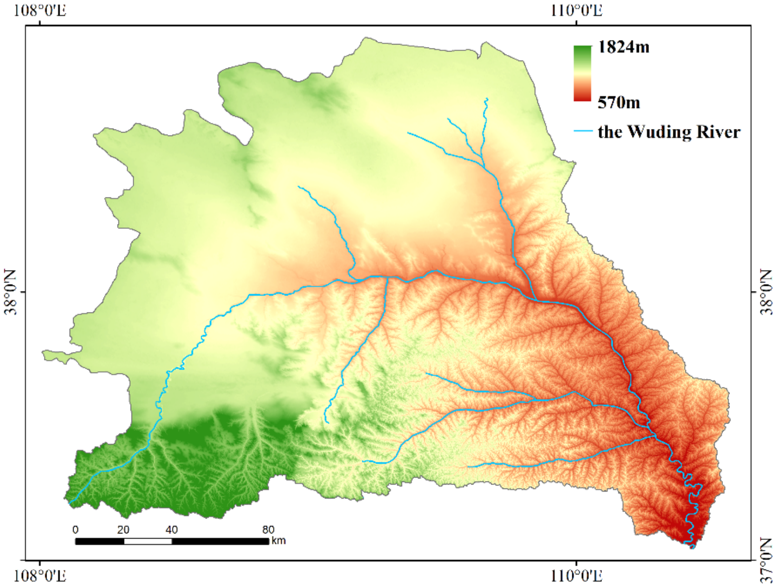

Fig 1. Location map of the Wuding River Basin

Remote sensing technology, with its advantages of large-scale, non-contact, high-frequency, and long-time-series observation, has become an efficient and mainstream approach for large-scale LAI retrieval, providing technical support for the quantitative acquisition of regional vegetation parameters[6]. At present, mainstream LAI retrieval methods worldwide are mainly divided into three categories. Empirical models establish statistical regression relationships based on remote sensing reflectance and measured LAI data. They feature simple structure, high computational efficiency, and easy implementation. However, such models highly rely on the representativeness of field samples and are significantly affected by land cover type, seasonal variation, viewing geometry, and atmospheric conditions, resulting in weak generalization ability and difficulty in meeting the requirements of LAI retrieval over complex underlying surfaces[2][7]. Pure radiative transfer models represented by the PROSAIL model are constructed based on the physical mechanism of radiative transfer in vegetation canopies. They can clearly reflect radiative interactions among the vegetation canopy, leaf, and soil background, with clear physical meaning and strong universality[1]. Nevertheless, in loess hilly and gully regions such as the Wuding River Basin, they are prone to ill-posed inversion due to topographic shadowing, strong reflectance interference from the soil background, and canopy heterogeneity. The temporal stability of retrieval results is insufficient, making it difficult to satisfy the needs of high-precision time-series monitoring. Hybrid radiative transfer models combine the physical mechanism of pure radiative transfer models with the data-driven advantages of machine learning and intelligent optimization algorithms. They not only retain the interpretability of physical models but also achieve the fitting accuracy and anti-interference capability of data-driven methods. Such models can effectively alleviate the inherent defects of single models and significantly improve the accuracy and robustness of LAI retrieval over complex underlying surfaces, thus becoming a frontier research direction in quantitative remote sensing retrieval of vegetation parameters in complex regions[3][8].

Against this background, constructing a hybrid radiative transfer model adapted to the complex underlying surface characteristics of the Wuding River Basin, breaking through the limitations of single-model inversion, realizing high spatiotemporal resolution and accurate temporal retrieval of LAI, and solving key technical problems in regional LAI dynamic monitoring has become an important scientific issue urgently to be addressed in the field of quantitative remote sensing and eco-hydrological research. It also provides scientific support for decision-making regarding watershed ecological protection and restoration.

2. Data

2.1. Field Measured Data

Field measured data used in this study were collected in the study area from July 21 to 31, 2024. After determining the sampling location, a square plot of 30 m × 30 m was manually delineated for LAI measurement. The instrument employed was a CI-110 Plant Canopy Analyzer. During the field campaign, a total of 63 sampling quadrats were measured.

2.2. Landsat Imagery

To achieve long-term time-series leaf area index retrieval in the Wuding River Basin from 2001 to 2024, Landsat series satellite remote sensing images were selected as the main data source in this study, including Landsat 5 TM, Landsat 7 ETM+, and Landsat 8 OLI data. These images cover a nearly 20-year observation period and provide stable and reliable data support for long-term vegetation dynamic monitoring. All images were processed with systematic radiometric calibration, atmospheric correction, and topographic correction to eliminate the influences of sensor differences, atmospheric attenuation, and topographic fluctuations on surface reflectance, so as to ensure the spectral consistency and comparability of data from different dates and sensors.

In terms of model construction and inversion strategy, Landsat 8 OLI images acquired in 2024 during the same period as field observations were used for the construction and parameter calibration of the hybrid radiative transfer model. On the premise of ensuring spectral quality and spatial resolution, the optimization and validation of key model parameters were completed. After the model was determined, the monthly composite images of the consistently preprocessed long-time-series Landsat 5, Landsat 7, and Landsat 8 images were input into the model to achieve continuous monthly LAI retrieval in the Wuding River Basin from 2001 to 2024, thereby obtaining a long-term, high-spatial-resolution spatiotemporal LAI dataset.

3. Research Methods

3.1. PROSAIL Model

The PROSAIL model is a classic physical model formed by coupling the leaf optical model PROSPECT and the canopy radiative transfer model SAIL. It is also one of the most widely used radiative transfer models in quantitative remote sensing inversion of vegetation parameters. The PROSPECT model is based on the plate waveguide theory and can simulate the reflectance and transmittance characteristics of leaves in the spectral range of 400–2500 nm. By inputting biochemical parameters such as leaf structure parameter, chlorophyll content, leaf water content, and dry matter content, it provides a sophisticated leaf optical basis for canopy radiative transfer simulation, as expressed in the following equation:

$$[refl(\lambda), tran(\lambda)] = PROSPECT(\lambda, C_{ab}, C_m, C_{bp}, C_w, C_{ar}, C_{ant}, N) \quad (1)$$

Where λ is the wavelength; C_{ab} is the chlorophyll content; C_m is the leaf dry matter content; C_{bp} is the leaf brown pigment content; C_w is the leaf equivalent water thickness; C_{ar} is the leaf carotenoid content; C_{ant} is the leaf anthocyanin content; N is the leaf structure parameter.

In contrast, the SAIL model simplifies the vegetation canopy as a one-dimensional homogeneous medium. It comprehensively considers factors including leaf area index, leaf angle distribution, hot-spot effect, soil background reflectance, and sun-view geometry, to simulate the absorption, scattering, and transfer processes of radiation within the canopy. The equation is given as follows:

$$\rho = SAIL(LAI, ALA, refl(\lambda), tran(\lambda), refs(\lambda), skyl(\lambda), \theta_s, \theta_o, \varphi) \quad (2)$$

Where λ is the wavelength; θ_s is the solar zenith angle; θ_o is the observation zenith angle; φ is the relative azimuth angle; LAI is the leaf area index; ALA is the average leaf angle; $refl(\lambda)$ and $tran(\lambda)$ are both simulated by the PROSPECT model; $refs(\lambda)$ is the soil (background) reflectance at wavelength λ; and $skyl(\lambda)$ is the fraction of diffuse skylight in the total incident radiation.

The coupled PROSAIL model enables a complete physical representation from leaf biochemical components and canopy structure to canopy reflectance spectra. With clear mechanistic interpretation and strong universality, it has been widely used in the inversion of vegetation structural and biochemical parameters such as LAI and chlorophyll content.

The parameters of the PROSAIL model used in this study are listed in Table 1.

Table 1. Parameters of the PROSAIL model used in this study

Model	Parameter	Value/Range	Step	Unit
PROSPECT	Leaf dry matter content(C_m)	0-0.02	0.001	g cm^{-2}
	Leaf chlorophyll content(C_{ab})	0-80	10	μg cm^{-2}
	Leaf equivalent water thickness(C_w)	0.035	-	g cm^{-2}
	Leaf carotenoid content(C_{ar})	0	-	g cm^{-2}
	Brown pigment fraction(C_{bp})	0	-	μg cm^{-2}
	Leaf anthocyanin content(C_{anth})	0	-	μg cm^{-2}
	Leaf structure index(N)	2.8	-	-
SAIL	Leaf area index(LAI)	0-6	0.02	m^2/m^2
	Average leaf angle(ALA)	20-70	10	°
	Soil factor(P_{soil})	0.3	-	-
	Hot spot parameter(H_{spot})	0.5/LAI	-	-
	Solar zenith angle(θ_i)	25.4658	-	°
	Observation zenith angle(θ_v)	0	-	°
	Sun-sensor azimuth angle(φ)	0	-	°

3.2. Random Forest Regression Model

Random Forest Regression is an ensemble learning-based predictive method that constructs multiple decision trees and aggregates their predictions through averaging or weighted averaging to produce the final output. By introducing randomness during training—including bootstrap sampling of observations and random feature selection—this model effectively mitigates the overfitting risks associated with individual decision trees while enhancing generalization capability and robustness against noise. Random Forest Regression demonstrates strong performance in handling high-dimensional data, capturing nonlinear relationships, and providing feature importance assessments, making it widely applicable to continuous numerical prediction tasks.

In this study, Random Forest Regression was employed to establish a nonlinear mapping relationship between PROSAIL-simulated spectral reflectance and Leaf Area Index (LAI). By learning from extensive sample data generated through PROSAIL model simulations, the intrinsic patterns between canopy reflectance and vegetation structural parameters were extracted, thereby enabling rapid, robust, and high-precision LAI retrieval.

4. Conclusion

4.1. Accuracy Validation

To verify the reliability of LAI inversion using the hybrid radiative transfer model, the measured LAI values were compared with the inverted LAI values, and the scatter plot is shown in the figure.

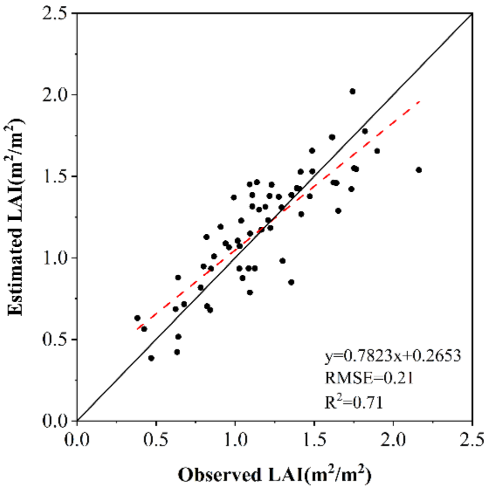

Fig 2. Analysis of predicted and measured values based on the hybrid RTM

The LAI inverted by the hybrid radiative transfer model in this study shows a significant linear correlation with ground-measured LAI, with a coefficient of determination R2=0.71 and root mean square error RMSE=0.21m2/m2, indicating a moderately high overall inversion accuracy. This demonstrates that the hybrid RTM method can effectively capture the spatiotemporal variation characteristics of vegetation canopy structure in the Wuding River Basin and presents good applicability and stability under complex underlying surface conditions. The fitting equation y=0.7823x+0.2653 reveals a certain systematic bias in the inversion model: the slope less than 1 suggests an obvious underestimation in the high LAI range, while the intercept greater than 0 reflects a certain overestimation in the low LAI range, which is mainly attributed to the complex impacts of topographic relief, soil background reflectance interference, and canopy heterogeneity on the radiative transfer process in the loess hilly-gully region. However, the overall error remains at a low level, illustrating that the hybrid RTM method, by integrating the advantages of physical mechanism and data-driven approaches, effectively alleviates the ill-posed inversion problem prone to traditional single radiative transfer models, and can provide reliable LAI data support for long-term vegetation dynamic monitoring and eco-hydrological effect assessment in the basin.

4.2. Comparison with Existing LAI Products

The LAI inverted by the hybrid radiative transfer model in this study was compared with existing LAI products (MODIS LAI and GLASS LAI), and the scatter plot is shown in the figure.

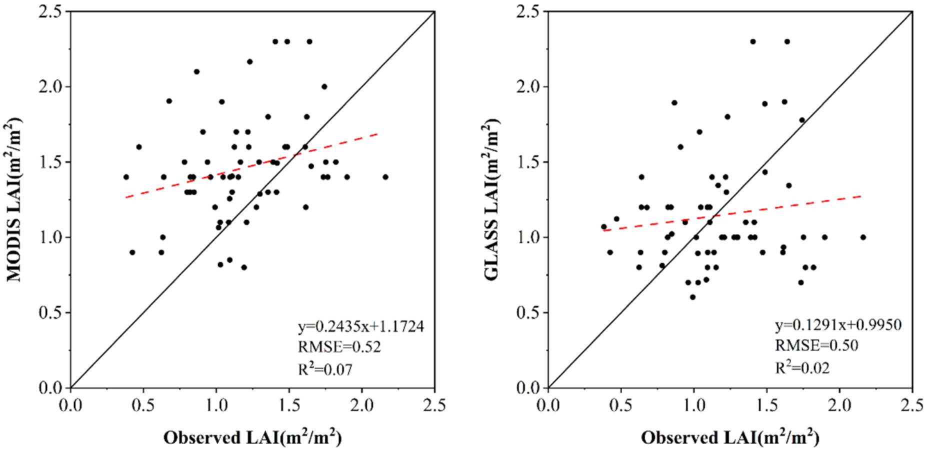

Fig 3. Evaluation of predicted values based on hybrid RTM and existing remote sensing products

Compared with MODIS LAI product, the inversion result in this study has R^2=0.07 and RMSE=0.52m^2/m^2; compared with GLASS LAI product, it has R^2=0.02 and RMSE=0.50m^2/m^2. The results show that, compared with existing remote sensing products, the LAI inverted by the RF-based hybrid radiative transfer model is more consistent with field-measured data and greatly outperforms existing products. In contrast, GLASS LAI and MODIS LAI show low consistency with field measurements. Notably, compared with GLASS LAI, the RMSE of LAI inverted by the mechanism-based RF model is reduced by 58%; compared with MODIS LAI, the RMSE is reduced by 59.6%. The poor consistency of GLASS LAI and MODIS LAI with field observations is mainly attributed to several factors. First, the complex mountainous terrain and strong spatial heterogeneity make it difficult for remote sensing data at coarse spatial scales to fully capture these fine topographic features. Second, biases may be introduced during the preprocessing of satellite observations, such as the loss of key information in cloud removal and image fusion steps. Third, the data retrieval methods also affect the accuracy of LAI estimation. For these reasons, GLASS and MODIS products exhibit large uncertainties in LAI estimation over mountainous areas. In comparison, the inversion method based on the hybrid radiative transfer model can better adapt to such spatial complexity, thereby improving the fitting performance and consistency with measured data.

4.3. Temporal Inversion Results

From the perspective of the spatiotemporal distribution pattern of LAI in typical months (March, June, August, October) from 2001 to 2024 in the Wuding River Basin, the vegetation canopy structure in the basin shows significant seasonal rhythms and interannual growth trends, and the spatial heterogeneity is highly coupled with the basin geomorphology and the implementation pattern of ecological restoration projects. At the seasonal scale, LAI values across the basin remain relatively low in March and October, with vegetation mainly in a littered or dormant state, and weak vegetation activity only in local river valleys. LAI begins to increase significantly in June, especially forming zonal high-value areas along the main stream and tributaries, reflecting the phenological rhythm of rapid vegetation green-up and growth after the onset of the rainy season.

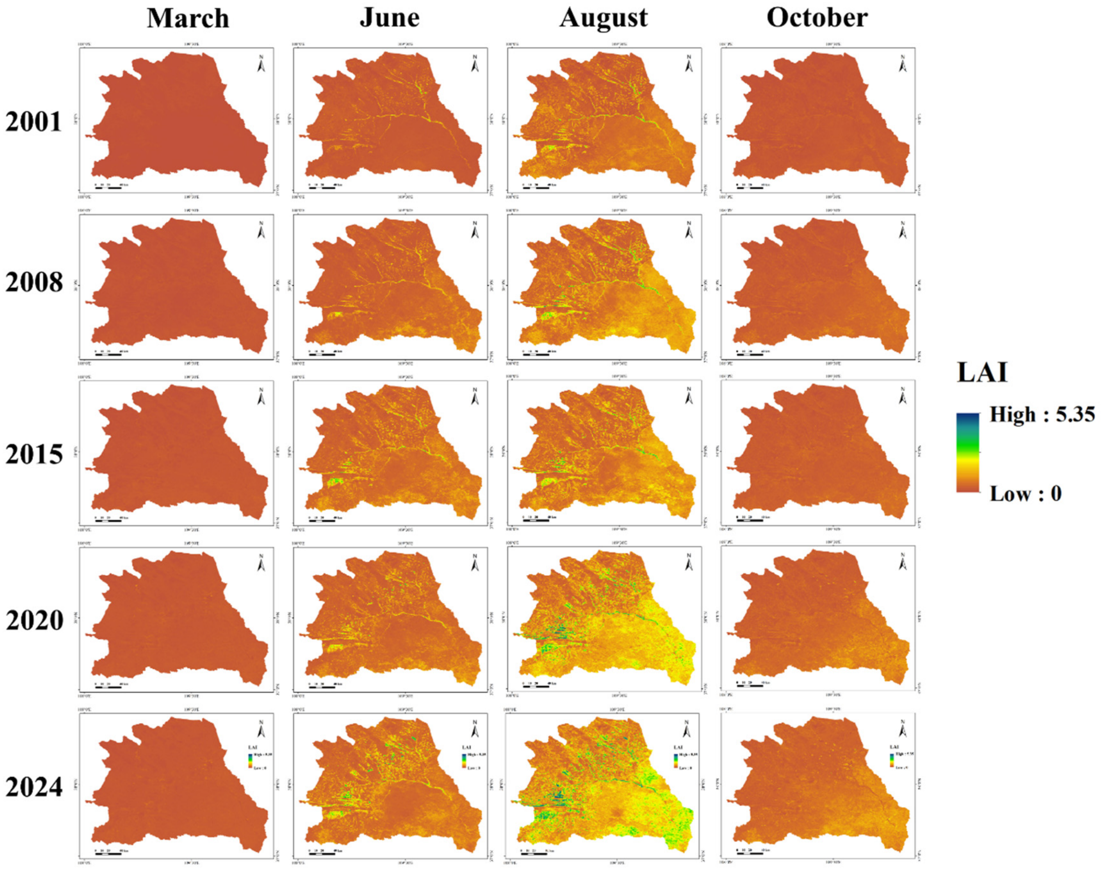

Fig 4. Time-series inversion results of typical months in the Wuding River Basin from 2001 to 2024

August marks the annual peak of LAI, with the high-value areas continuously expanding and extending to the loess hilly-gully regions in the southern and eastern parts of the basin, which is highly consistent with the seasonal characteristics of the most abundant hydrothermal conditions and the strongest photosynthesis, reflecting the typical temperate semi-arid vegetation phenology in the Wuding River Basin: initiation in late spring and early summer, peak in midsummer, and rapid decline in autumn. At the interannual scale, the scope of high LAI values in the same season continuously expanded and the numerical gradient increased from 2001 to 2024. In particular, the high LAI areas in August of 2020 and 2024 expanded significantly to the southeast and south of the basin compared with 2001. This change is highly consistent with the long-term effects of ecological restoration projects such as the Grain for Green Project, sand prevention and desertification control on the Loess Plateau, indicating that vegetation coverage and canopy structure in the basin have been continuously improved over the past 20 years, with remarkable ecological restoration effects. Meanwhile, high LAI areas are always concentrated in the valley beaches and artificial forest-grass areas along the main stream and major tributaries of the Wuding River, while LAI in the wind-sand area in the north and hilly-gully area in the west remains at a low level for a long time, reflecting the constraints of topography, soil texture and water resource distribution on vegetation growth, and also indicating that the implementation effect of ecological restoration projects is more prominent in areas with favorable water resources. Overall, the spatiotemporal pattern of LAI inverted by the hybrid radiative transfer model not only accurately characterizes the seasonal phenological rhythm and interannual variation trend of vegetation in the Wuding River Basin, but also profoundly reveals the spatial differentiation characteristics of vegetation shaped by the combined effects of ecological restoration projects and natural environmental constraints, providing reliable spatial data support for quantitatively evaluating the effects of ecological restoration on the Loess Plateau and analyzing the vegetation-water-sediment coupling mechanism.

4.4. Interannual Variation Characteristics

From 2001 to 2024, the annual mean LAI in the Wuding River Basin showed a significant increasing trend with periodic fluctuations, which directly reflects the long-term improvement of vegetation coverage and ecosystem quality in the basin. During the study period, the annual mean LAI of the whole basin started from approximately 0.25m^2/m^2 in 2001, experienced slow growth from 2001 to 2008, rapid increase from 2008 to 2016, and high-level fluctuations after 2016, reaching nearly 0.60m^2/m^2 by 2024 with an increase of more than 130%, indicating that vegetation growth status, canopy structure and biomass in the Wuding River Basin have been greatly improved over the past two decades. The interannual variation also presented obvious stage characteristics: from 2001 to 2004, the basin was in the initial stage of vegetation restoration with relatively gentle LAI growth; from 2005 to 2012, with the continuous implementation of ecological projects such as the Grain for Green Program and comprehensive small watershed management, the LAI growth rate accelerated significantly, forming a key stage for vegetation coverage improvement; a periodic peak of LAI occurred around 2016, and although slight fluctuations followed, LAI remained at a high level, reflecting the superimposed influence of long-term accumulated ecological restoration effects and interannual climate fluctuations.

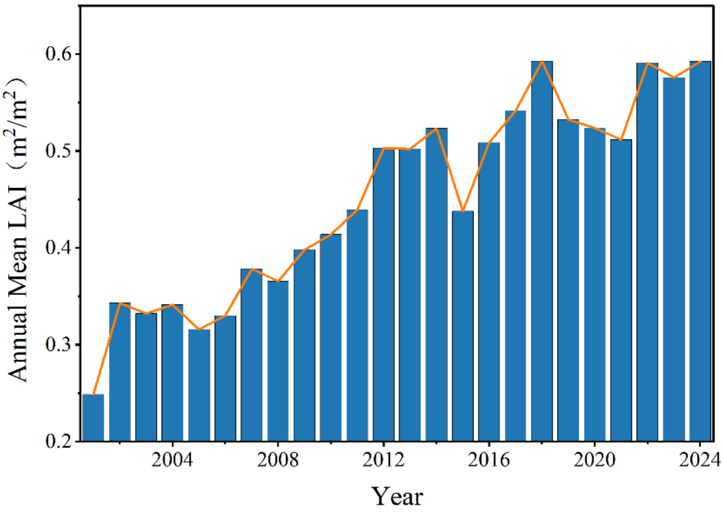

Fig 5. Interannual variation of LAI in the Wuding River Basin

4.5. Monthly Variation Characteristics

From 2001 to 2024, the monthly mean LAI in the Wuding River Basin exhibited a highly regular unimodal intra-annual rhythm, with the curve repeating stably on a 12-month cycle. Peaks were concentrated in July and August each year, corresponding to the midsummer period when hydrothermal conditions were most abundant and vegetation photosynthesis was strongest. Troughs occurred steadily in January and February, reflecting the physiological characteristics of winter vegetation dormancy and the lowest canopy activity. This accurately depicts the complete monthly growth cycle of vegetation in temperate semi-arid regions: rapid green-up in spring, peak in summer, gradual decline in autumn, and low values maintained in winter. Compared with the seasonal scale, monthly fluctuations show more detailed characteristics, clearly capturing the rapid increase in April-May and the gradual decrease in September-October. Over time, the difference between annual peaks and troughs continued to expand, indicating that the improvement of vegetation canopy structure further amplified monthly growth differences. This more precisely reveals the response characteristics of basin vegetation to monthly changes in climatic factors such as precipitation and temperature, providing high-resolution time-series support for the accurate delineation of vegetation phenology and the monthly simulation of eco-hydrological processes.

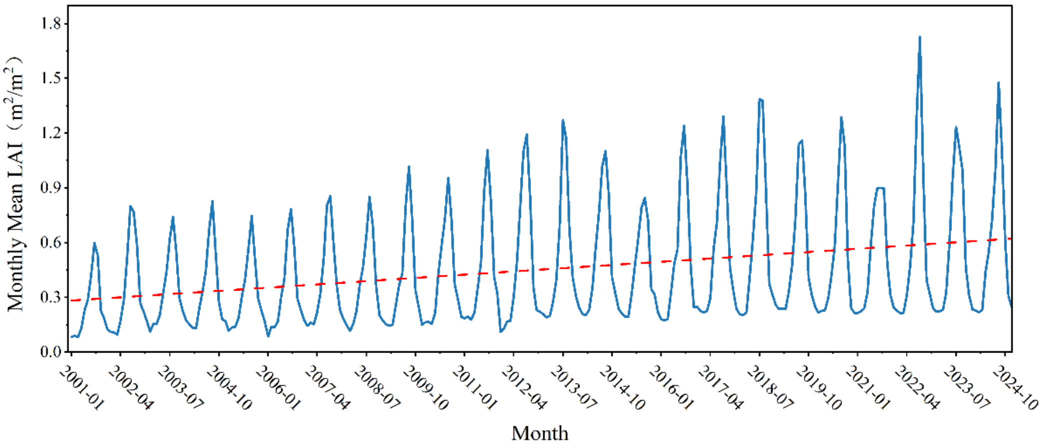

Fig 6. Monthly variation of LAI in the Wuding River Basin

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