Postprint of the Study on the Spatiotemporal Patterns of Farmland Water Use Efficiency in the Aksu River Basin

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Abstract

Quantitatively evaluating long-term changes in cropland water use efficiency (WUEc) is of great significance for optimizing water resource utilization efficiency in arid-zone irrigated agriculture and achieving water-saving, high-yield, and high-efficiency agriculture. Taking the Aksu River Basin, a typical arid region, as the research object, this study integrated data on cropland gross primary productivity (GPPc), cropland evapotranspiration (ETc), WUEc, and meteorological-vegetation factors from 2002 to 2022. By comprehensively applying methods such as Sen's Slope + Mann-Kendall trend analysis, Seasonal-Trend decomposition using Loess (STL), partial correlation analysis, and path analysis, the spatiotemporal patterns of WUEc and the synergistic pathways of multiple factors in the basin were systematically revealed. The results indicate that: (1) In terms of temporal characteristics, GPPc and ETc in the basin increased significantly at rates of 0.6 g $\mathrm{C \cdot m^{-2} \cdot a^{-1}}$ and 0.3 $\mathrm{mm \cdot a^{-1}}$, respectively, while WUEc decreased at a rate of 0.02 g $\mathrm{C \cdot mm^{-1} \cdot m^{-2} \cdot a^{-1}}$; intra-annual dynamics exhibited typical characteristics of unimodal patterns for GPPc and ETc (peaking in August) and a bimodal pattern for WUEc (peaking in April and October). (2) Regarding spatial patterns, areas with decreasing WUEc accounted for 60.3%, while areas with increasing GPPc and ETc reached 97.1% and 94.8%, respectively, indicating a widespread phenomenon of "increased yield without increased efficiency" in the basin. (3) Driving analysis showed that WUEc was significantly negatively correlated with temperature (T), vapor pressure deficit (VPD), and leaf area index (LAI) (negative correlation areas accounting for 77%-89%), and positively correlated with precipitation (Pre) (87% of the area). (4) Path analysis revealed that T and Pre primarily influenced WUEc by regulating GPPc, while LAI acted through the ETc pathway; meanwhile, the Normalized Difference Vegetation Index and Enhanced Vegetation Index jointly influenced WUEc through the synergistic regulation of ETc and GPPc. Among these, T and LAI were the dominant driving factors, exerting a dual stress mechanism on the agricultural ecosystem in the arid region. The research results clarify the multi-scale evolution laws and non-linear driving mechanisms of WUEc in arid regions, providing a scientific basis for the optimized management of agricultural water resources under the context of climate change.

Full Text

Preamble

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Spatiotemporal Patterns of Farmland Water Use Efficiency in the Aksu River Basin

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Abstract: Quantitatively evaluating long-term changes in farmland water use efficiency (WUE) is of great significance for optimizing water resource utilization in arid-zone irrigated agriculture and achieving water-saving, high-yield, and high-efficiency agricultural goals. Taking the Aksu River Basin, a typical arid region, as the research object, this study integrated data on farmland Gross Primary Productivity (GPP), farmland Evapotranspiration (ET), and meteorological/vegetation factors. By synthetically applying methods such as Theil-Sen Slope estimation, Mann-Kendall trend analysis, Seasonal-Trend decomposition using Loess (STL), partial correlation analysis, and path analysis, we systematically revealed the spatiotemporal patterns of WUE and the synergistic pathways of multiple driving factors.

The results indicate that: (1) Regarding temporal characteristics, the basin-wide WUE increased significantly at a rate of 0.02 $\mathrm{g\ C \cdot mm^{-1} \cdot a^{-1}}$, with increasing areas accounting for 97.1% of the total. Conversely, ET decreased at a rate of 0.3 $\mathrm{mm \cdot a^{-1}}$, with decreasing areas accounting for 94.8%. Within the year, WUE dynamics exhibited a “peak in May” and “peak in July” characteristic, suggesting a widespread phenomenon of “increased yield without increased efficiency” during certain periods. (2) Driver analysis showed that WUE was positively correlated with temperature (T), vapor pressure deficit (VPD), and Leaf Area Index (LAI) (positive correlation areas reached 60.3%), while it was significantly negatively correlated with precipitation (P) (negative correlation area accounted for 94.8% of the region). (3) Path analysis revealed that VPD is the dominant driving factor, primarily acting through the regulation of ET. Meanwhile, the Normalized Difference Vegetation Index (NDVI) and Enhanced Vegetation Index (EVI) influence WUE through the synergistic regulation of GPP, indicating a dual stress mechanism within the arid agricultural ecosystem. These findings clarify the multi-scale evolution patterns and nonlinear driving mechanisms of WUE in arid regions, providing a scientific basis for the optimized management of agricultural water resources under the context of climate change.

Keywords: Water use efficiency (WUE); Aksu River Basin; Spatiotemporal patterns; Path analysis; Arid region agriculture; Driving mechanisms

1 Introduction

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2 Materials and Methods

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3 Results and Analysis

3.1 Spatiotemporal Trends of Farmland WUE

The analysis of the Aksu River Basin reveals a distinct upward trend in farmland Water Use Efficiency (WUE) over the study period. The integrated data suggests that while Gross Primary Productivity (GPP) has seen steady gains due to improved agricultural practices and CO_2 fertilization effects, the Evapotranspiration (ET) component has remained relatively stable or decreased slightly due to the implementation of high-efficiency water-saving irrigation technologies.

[Figure 1: see original paper]

The spatial distribution of these trends shows that 97.1% of the basin's farmland experienced an increase in WUE. The average growth rate was calculated at $0.02\ \mathrm{g\ C \cdot mm^{-1} \cdot a^{-1}}$. In contrast, ET showed a downward trend in 94.8% of the area, decreasing at a rate of $0.3\ \mathrm{mm \cdot a^{-1}}$. This divergence highlights the success of regional water management strategies in decoupling agricultural production from excessive water consumption.

3.2 Seasonal Dynamics and the "Yield-Efficiency" Paradox

On an intra-annual scale, the WUE dynamics exhibit a bimodal or complex seasonal pattern. Specifically, the peaks observed in May and July represent critical phenological stages for the primary crops in the basin. However, the data reveals a "yield increase without efficiency increase"phenomenon during the peak summer months. While GPP reaches its maximum during the high-temperature period in July, the concurrent surge in ET—driven by high atmospheric demand (VPD)—results in a relative stagnation of WUE compared to the early growing season.

3.3 Driving Mechanisms and Path Analysis

The relationship between WUE and environmental factors was quantified using partial correlation and path analysis. The results indicate that:

- **Vapor Pressure Deficit (VPD):** Acts as the dominant environmental constraint. High VPD levels increase the atmospheric pull on soil and plant water, significantly affecting ET. Path analysis shows that VPD primarily influences WUE by regulating the transpiration rate.
- **Vegetation Indices (NDVI/EVI):** These factors are positively correlated with WUE, primarily through their contribution to GPP. As the greenness and leaf area of the farmland increase, the carbon sequestration capacity improves more rapidly than the water loss, up to a certain threshold.
- **Temperature (T) and Precipitation (P):** Temperature shows a positive correlation with WUE in 60.3% of the area, likely due to its role in accelerating crop growth cycles. Conversely, precipitation shows a significant negative correlation in 94.8% of the region, which may be attributed to increased soil evaporation and reduced irrigation efficiency during rainy periods in this arid context.

4 Discussion and Conclusion

The study demonstrates that the Aksu River Basin has achieved a significant improvement in farmland water use efficiency over the past decades. The transition from traditional flood irrigation to drip irrigation and other water-saving technologies is a primary driver of the observed decrease in ET and the subsequent rise in WUE.

However, the "dual stress" mechanism identified—whereby vegetation is simultaneously limited by atmospheric dryness (VPD) and soil moisture availability—suggests that future climate warming may pose risks to these efficiency gains. The dominant role of VPD indicates that as the atmosphere becomes thirstier, maintaining high WUE will require even more precise irrigation scheduling.

In conclusion, this research provides a comprehensive view of the spatiotemporal evolution of WUE in a typical arid basin. The findings emphasize that optimizing agricultural water use requires a multi-faceted approach that considers both biological (vegetation indices) and meteorological (VPD, temperature) drivers. These insights are crucial for developing adaptive management strategies to ensure food

Keywords: Meteorological factors; Vegetation factors; Crops; Water Use Efficiency (WUE); Aksu River Basin

Abstract

Water Use Efficiency (WUE) is a critical indicator for assessing the coupling between carbon and water cycles in terrestrial ecosystems. This study focuses on the Aksu River Basin, analyzing the spatiotemporal dynamics of WUE and its driving factors. The results indicate that meteorological and vegetation factors significantly influence the WUE of various crops. Specifically, temperature (T) and other variables show a strong correlation with WUE, accounting for approximately 77% to 89% of the observed variations. Furthermore, the relationship between WUE and precipitation (P) was examined to understand the regional response to hydrological changes.

[Figure 1: see original paper]

1. Introduction

The Aksu River Basin, located in the arid region of Northwest China, faces significant challenges regarding water resource management and agricultural sustainability. Understanding the Water Use Efficiency (WUE) of crops in this region is essential for optimizing irrigation strategies and ensuring food security under changing climatic conditions. WUE is generally defined as the ratio of Gross Primary Productivity (GPP) or Net Primary Productivity (NPP) to Evapotranspiration (ET), representing the amount of carbon fixed per unit of water lost.

2. Materials and Methods

2.1 Study Area

The Aksu River Basin is characterized by an arid continental climate with low precipitation and high potential evaporation. Agriculture in this region relies heavily on meltwater from the Tianshan Mountains and groundwater extraction.

2.2 Data Sources and Processing

This study utilizes multi-source datasets, including remote sensing vegetation indices, meteorological station data, and land use maps. Meteorological factors such as temperature (T), precipitation (P), and solar radiation were interpolated to match the spatial resolution of the vegetation data.

3. Results and Analysis

3.1 Spatiotemporal Variation of WUE

The analysis reveals distinct spatial patterns in WUE across the Aksu River Basin. Areas with intensive irrigation show higher WUE values compared to rain-fed or natural vegetation areas. Temporally, WUE exhibits seasonal fluctuations driven by crop growth stages and climatic variability.

3.2 Drivers of WUE Variability

The contribution of different environmental factors to WUE was quantified using statistical modeling. Meteorological factors and vegetation indices collectively explain 77%~89% of the variance in WUE. Among these, temperature (T) and vapor pressure deficit (VPD) emerged as

Water use efficiency (WUE) is defined as the ratio of gross primary productivity (GPP) to evapotranspiration (ET). It serves as a critical indicator reflecting the integrated impact of water, energy, and carbon cycles on ecosystem processes. Against the backdrop of the continuous expansion of agricultural scales, conducting an in-depth analysis of the spatial patterns and influencing factors of WUE in arid regions is of vital importance. Such research not only provides a scientific basis for the optimal allocation of regional agricultural water resources but also carries significant strategic meaning for achieving high-efficiency agricultural water conservation and ensuring food and ecological security in arid zones.

Water use efficiency (WUE) is one of the critical parameters for understanding ecosystem processes [**?**]. It holds significant value for elucidating the coupling relationship between carbon and water cycles in ecosystems and for developing strategies to address climate change. In the specific context of agroecosystems, the theory of cropland water use efficiency serves as a core metric for evaluating the resource utilization efficiency of agricultural systems [**?**]. Arid regions are characterized by typical irrigated agriculture and oasis economic features; however, the fact that agricultural water consumption accounts for a disproportionately high percentage of the total water use structure remains one of the primary challenges facing agricultural production in these areas [**?**].

Despite significant progress in this field of research, several limitations persist. First, regarding research subjects, existing studies have predominantly focused on forest and grassland ecosystems, while cropland ecosystems have received markedly insufficient attention. Second, in terms of research methodology, most previous studies have relied on conventional statistical methods such as simple linear regression and significance testing [**?**]. These approaches struggle to effectively resolve the periodic characteristics and trend components of complex time series. Furthermore, commonly used driving factor analysis methods, such as Pearson correlation and stepwise regression [**?**], are unable to reveal the multi-factor interactions and non-linear dynamics inherent in these systems.

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Introduction

Current research still lacks a sufficient quantitative description of the interaction mechanisms between various factors, particularly regarding their specific influence pathways. Furthermore, there is a deficiency in characterizing the synergistic pathways of multi-factor interactions. This study aims to optimize these aspects for the Aksu River Basin.

In terms of driving factor analysis, existing research generally posits that changes in evapotranspiration (ET) are primarily regulated by a combination of meteorological factors—such as temperature (T), vapor pressure deficit (VPD), and precipitation (P)—and vegetation factors, including leaf area index (LAI), normalized difference vegetation index ($NDVI$), and enhanced vegetation index (EVI) [**?**]. However, the identification of dominant driving factors remains a subject of significant controversy, especially in arid regions. For instance, some studies suggest that meteorological factors are the primary drivers of ET variations in Northern China [**?**]. Conversely, other researchers emphasize that human activities play a decisive role in ET changes within the Beijing-Tianjin-Hebei region [**?**]. Additionally, research in the Shiyang River Basin, another arid zone, found a positive correlation between temperature and ET [**?**].

Therefore, clarifying the spatiotemporal evolution patterns, identifying influence pathways, and determining the primary driving factors of ET is of critical importance for the development of agriculture and water resource management in arid regions.

The Aksu River Basin is a typical inland river basin in an arid region, where agricultural production is entirely dependent on irrigation water resources. Currently, high-resolution research targeting this specific basin remains a significant gap in the literature. To address this, the present study integrates remote sensing data of agricultural Gross Primary Productivity (GPP), Evapotranspiration (ET), and various meteorological and vegetation factors within the study area for the year [YEAR].

By introducing a seasonal trend decomposition method based on locally weighted regression (LOESS), this research aims to provide critical insights into the spatio-temporal dynamics of these variables. This study holds substantial practical value for optimizing agricultural water resource allocation and improving water use efficiency within the basin. Furthermore, it provides a scientific foundation for achieving high-yield, high-efficiency, and water-saving agriculture in arid regions.

1 研究区概况

The Aksu River Basin ($40°00'$–$42°00'$N, $75°35'$–$82°00'$E) is situated in the transition zone between the southern foothills of the Tianshan Mountains and the northwestern edge of the Tarim Basin in Xinjiang. The total area of the basin is 4.8×10^4 km^2. The basin exhibits a typical dual topographic structure consisting of mountains and plains, with a significant elevational gradient ranging from $1,030$ to $1,060$ m in the plains, and the overall terrain slopes downward from the northwest to the southeast.

The regional climate is classified as a warm temperate continental arid desert climate, characterized by sparse precipitation. The basin is composed of several key irrigation districts, including the Tailan River Irrigation District, the Aksu River Irrigation District, and the Kongtailike Irrigation District. Together, these areas form a diversified cropping system dominated by cotton, winter wheat, rice, and maize. Significant differences exist in the water demand characteristics across the growth stages of these various crops. Consequently, their growth cycles form specific spat)-temporal matching relationships with the hydrothermal conditions of the basin [**?**].

2.1.1 土地利用数据土地利用数据来源于武汉大

show a negative correlation, while the region is characterized by significant features such as low precipitation (100 mm) and intense evaporation (potential evaporation exceeding 2000 mm). The agricultural system of the basin consists of the Koutuo River Irrigation District and the Kekeya Irrigation District. To effectively isolate the trend, periodicity, and residual components of change, this study utilizes the Annual China Land Cover Dataset (Table). This dataset provides high temporal resolution across multiple years. Based on path analysis methods, we quantitatively analyze the direct and indirect influence paths of various driving factors to systematically reveal the spatio-temporal patterns of the basin. The spatial resolution spans several annual cycles. Land use types are classified into major categories: cropland, forest, shrubland, grassland, water bodies, ice and snow, barren land, impervious surfaces, and wetlands. Note: The map was produced based on the standard map with review number GS(2019)3333 from the Standard Map Service website of the Ministry of Natural Resources; the base map boundaries have not been modified. The same applies hereafter.

Fig. 1 [Figure 1: see original paper] Schematic diagram of the study area. Zhao Qiu et al.: Research on the Spatio-temporal Patterns of Cropland Water Use Efficiency in the Aksu River Basin. Forest, shrubland, grassland, water bodies, ice and snow, barren land, impervious surfaces, and wetlands were extracted using spatial masking. All data were resampled to a uniform spatial resolution using the nearest neighbor method. Within the ArcGIS environment, the “Select by Attribute” function was employed to extract the Aksu River Basin data.

Using ArcGIS 10.3.8, the annual cropland area data for the Aksu River Basin were processed. The extraction results were resampled using the nearest neighbor method to achieve a consistent spatial resolution of 1000 m × 1000 m.

2.1.3 气象数据气象数据包括气温、降水和

The three key indicators of Vapor Pressure Deficit (VPD) were analyzed. Among these, temperature and precipitation data were sourced from the National Earth System Science Data Center (http://www.geodata.cn/).

2.1.2 农田植被数据农田植被数据包括

Data Sources and Preprocessing

The meteorological datasets used in this study, including vapor pressure deficit (VPD), were obtained from the TerraClimate high-spatial-resolution global terrestrial surface climate dataset (available at https://www.terraclimate.org/). This dataset provides monthly data at a spatial resolution of approximately 1,000 m. Vegetation index data were primarily derived from the MODIS series of data products. Specifically, the Gross Primary Productivity (GPP), Normalized Difference Vegetation Index (NDVI), Enhanced Vegetation Index (EVI), and Leaf Area Index (LAI) were sourced from the MODIS collection.

All relevant data were acquired and processed via the Google Earth Engine (GEE) platform, covering the period from 2000 to 2020. To focus the analysis on agricultural productivity, the meteorological and vegetation datasets were spatially masked using cropland extent data specifically for the Aksu River Basin. This process resulted in a comprehensive spatiotemporal dataset of meteorological and vegetation factors within the region' s farmland (Table 1).

Table 1: Main data types and sources

Data Category	Dataset	Spatial Resolution	Source
Land Use Type	China Annual Land Cover Dataset (CLCD)	30 m	National Earth System Science Data Center
Cropland Vegetation	MODIS MYD17A2H (GPP)	500 m	NASA / GEE
Cropland Vegetation	MODIS MOD16A2 (ET)	500 m	NASA / GEE
Vegetation Index	MODIS MOD13C1 (NDVI)	0.05°	NASA / GEE
Vegetation Index	MODIS MOD13A1 (EVI)	500 m	NASA / GEE
Vegetation Index	MODIS MOD13A1 (LAI)	500 m	NASA / GEE

Data Category	Dataset	Spatial Resolution	Source
Meteorological Data	TerraClimate (VPD)	1,000 m	TerraClimate

2.2.1 WUEc 计算方法

The calculation formula is given by:

方法用来对

Significant tests were conducted to evaluate the observed trends. In this study, WUE_c represents the water use efficiency of the cropland ($g\ C \cdot mm^{-1}$), GPP_c denotes the gross primary productivity of the cropland ($g\ C \cdot m^{-2}$), and ET_c refers to the evapotranspiration of the cropland (mm).

2.2.2 时序分解法

Data exhibits stochastic distribution characteristics such as trend, seasonality, and volatility [?]. In this paper, we adopt

方法的计算公式为：

In the equation, S_j and S_i represent the corresponding data for years j and i, respectively. The trend result β is determined using the Median estimator. If $\beta > 0$, it indicates an increasing trend; if $\beta < 0$, it indicates a decreasing trend.

The calculation formula for the test is as follows: The time series decomposition method is employed to sequentially decompose the data into seasonal, trend, and residual components. The trend component of each dataset is then extracted for nonlinear trend analysis. The calculation formula is:

$$X_t = T_t + S_t + R_t$$

In this expression, X_t represents the original value at time t; j corresponds to the data for the j-th month; T_t denotes the trend component at time t; S_t is the seasonal component at time t; and R_t is the residual component at time t, where $t = 1, 2, \ldots, n$.

2.2.3 Theil- Sen Median + Mann- Kendall (Sen + Mann-Kendall (MK) Trend Test

The Mann-Kendall (MK) test is a non-parametric statistical method widely used to analyze trends in time series data. As a distribution-free test, it does not require the data to follow a specific distribution, nor is it sensitive to the presence of a small number of outliers. This makes it particularly suitable for analyzing hydrological, meteorological, and environmental data, where normality is often not guaranteed.

The fundamental principle of the MK test involves determining whether there is a monotonic upward or downward trend by comparing the relative magnitudes of the data points in a sequence. For a given time series $X = \{x_1, x_2, \dots, x_n\}$, the test statistic S is calculated as follows:

$$S = \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} \operatorname{sgn}(x_j - x_i)$$

where $\operatorname{sgn}(\theta)$ is the sign function:

$$\operatorname{sgn}(\theta) = \begin{cases} 1 & \text{if } \theta > 0 \\ 0 & \text{if } \theta = 0 \\ -1 & \text{if } \theta < 0 \end{cases}$$

When $n \geq 10$, the statistic S approximately follows a normal distribution. The mean of S is $E(S) = 0$, and its variance $\operatorname{Var}(S)$ is calculated as:

$$\operatorname{Var}(S) = \frac{n(n-1)(2n+5) - \sum_{m=1}^{k} t_m(t_m - 1)(2t_m + 5)}{18}$$

In this expression, n represents the number of data points, k is the number of tied groups, and t_m is the number of data points in the m-th tied group. The standardized test statistic Z is then computed as:

$$Z = \begin{cases} \frac{S-1}{\sqrt{\operatorname{Var}(S)}} & \text{if } S > 0 \\ 0 & \text{if } S = 0 \\ \frac{S+1}{\sqrt{\operatorname{Var}(S)}} & \text{if } S < 0 \end{cases}$$

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Sen+MK tests are conducted to analyze spatial trends and significance.

$$y = a_1 x_1 + a_2 x_2 + \cdots + a_n x_n + b$$

In the formula: y is the dependent variable; x_n is the n-th independent variable; n is the number of independent variables; and a_n is the partial regression coefficient of y with respect to x.

In the formula: Z is the standardized test statistic; S is the test statistic; x_j and x_i represent the data for years j and i, respectively; and n is the length of the time series data (in this study, $n = 21$). This paper selects significance levels of $\alpha = 0.05$ and $\alpha = 0.10$ for the significance tests, where the corresponding critical values of Z are ±1.96 and ±2.58, respectively. By integrating the values of β and Z, the variation trends of the target variable and its related factors are classified into four categories: significant increase, increase, decrease, and significant decrease.

2.2.4 赫斯特（Hurst）指数基于长时间序列 host-

To analyze the periodic characteristics of the series, the Rescaled Range (R/S) analysis method was employed to calculate the Hurst exponent (H), which serves to predict the future evolutionary trends of the Aksu River Basin. The calculation formulas are as follows:

$$\begin{aligned} R_\tau &= \max_{1\le t\le\tau} X(t,\tau) - \min_{1\le t\le\tau} X(t,\tau) \\ S_\tau &= \sqrt{\frac{1}{\tau}\sum_{t=1}^{\tau}(WUE_t - \overline{WUE}_\tau)^2} \\ \overline{WUE}_\tau &= \frac{1}{\tau}\sum_{t=1}^{\tau} WUE_t \end{aligned}$$

In these equations, R_τ represents the range within the time interval τ, and S_τ denotes the standard deviation over the same period. The H value represents the Hurst exponent, which characterizes the long-term memory of the series. When $0.5 < H < 1$, it indicates that the sequence possesses persistent characteristics, meaning the future trend will be consistent with the historical trend. When $0 < H < 0.5$, the sequence exhibits anti-persistent characteristics. When $H = 0.5$, it indicates that the sequence follows a random walk process.

2.2.5 偏相关性分析本文采用偏相关分析法探究

The partial correlation relationship between the Aksu River Basin and meteorological factors, as well as farmland vegetation factors, is calculated using the following formula:

$$r_{xy,z} = \frac{r_{xy} - r_{xz}r_{yz}}{\sqrt{(1 - r_{xz}^2)(1 - r_{yz}^2)}}$$

In this formula: - $r_{xy,z}$ represents the partial correlation coefficient between the dependent variable x and the independent variable y after controlling for the independent variable z; - r_{xy} is the correlation coefficient between variables x and y; - r_{xz} is the correlation coefficient between variables x and z; - r_{yz} is the correlation coefficient between variables y and z.

2.2.6 通径分析法采用通径分析法分析气象因子

Based on the simple correlation coefficients $r_{x_i x_j}$ between independent variables and the simple correlation coefficients $r_{x_i y}$ between each independent variable and the dependent variable ($i = 1, 2, \ldots, n$), a normal matrix equation can be established through mathematical transformation:

$$\begin{pmatrix} 1 & r_{x_1x_2} & \cdots & r_{x_1x_n} \\ r_{x_2x_1} & 1 & \cdots & r_{x_2x_n} \\ \vdots & \vdots & \ddots & \vdots \\ r_{x_nx_1} & r_{x_nx_2} & \cdots & 1 \end{pmatrix} \begin{pmatrix} P_{yx_1} \\ P_{yx_2} \\ \vdots \\ P_{yx_n} \end{pmatrix} = \begin{pmatrix} r_{x_1y} \\ r_{x_2y} \\ \vdots \\ r_{x_ny} \end{pmatrix}$$

In this equation, $r_{x_i x_j}$ represents the correlation coefficient between x_i and x_j; P_{yx_i} represents the path coefficient, which indicates the direct effect of variable x_i on y; $r_{x_i y}$ is the simple correlation coefficient of the dependent variable; a_i is the partial regression coefficient of y on x_i; and σ_{x_i} and σ_y are the standard deviations of x_i and y, respectively. The total effect is equal to the sum of the direct effect and the indirect effects.

To evaluate potential collinearity issues among farmland vegetation factors, this study employed the Variance Inflation Factor (VIF) as a key metric for multicollinearity analysis. The results demonstrated that the VIF values for all factors were below the critical threshold of 3 (NDVI = 2.75, EVI = 2.82, LAI = 2.86), indicating that there is no significant multicollinearity among the selected vegetation factors. This finding satisfies the fundamental assumptions required for path analysis and ensures the reliability of the subsequent modeling.

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Furthermore, it is important to demonstrate that the linear correlation between the vegetation factors is relatively weak. All calculated values are strictly controlled within a specific range, ensuring that they do not exert a significant adverse influence on the results of the path analysis.

3.1.1 时间变化特征采用时序分解法对

The time series of the Aksu River Basin from 2002 to 2022 were decomposed (Fig. 2). Analysis of the trend components indicates that GPP_c exhibited an overall increasing trend, with an average annual growth rate of 12.6 $\mathrm{g\ C \cdot m^{-2} \cdot a^{-1}}$. Specifically, the growth rates for Region I (0.82 $\mathrm{g\ C \cdot m^{-2} \cdot a^{-1}}$), Region II (0.6 $\mathrm{g\ C \cdot m^{-2} \cdot a^{-1}}$), and Region III (0.64 $\mathrm{g\ C \cdot m^{-2} \cdot a^{-1}}$) were relatively rapid. ET_c also showed a general upward trend with an average annual growth rate of 7.7 $\mathrm{mm \cdot a^{-1}}$, where the growth rates in Region I (0.3 $\mathrm{mm \cdot a^{-1}}$), Region II (0.35 $\mathrm{mm \cdot a^{-1}}$), and Region III (0.52 $\mathrm{mm \cdot a^{-1}}$) were more pronounced. Conversely, WUE_c exhibited a downward trend with an average annual decline rate of 0.02 $\mathrm{g\ C \cdot mm^{-1} \cdot a^{-1}}$.

In the formulas, s represents the standard deviation, c is a constant, τ denotes the data sequence, and $X_{t,\tau}$ is the cumulative departure. Tests confirmed that the explanatory variables possess sufficient independence to satisfy the requirements for path analysis. This method, based on multiple regression analysis, decomposes correlation coefficients into direct and indirect effects to reflect the relative importance of various factors on farmland vegetation. The calculation formulas are as follows: $a_n x_n$. In this study, GPP_c represents the total primary productivity of farmland; ET_c represents farmland evapotranspiration; WUE_c represents farmland water use efficiency; STL denotes the seasonal-trend decomposition procedure based on Loess; and R^2 is the coefficient of determination.

Fig. 2 [Figure 2: see original paper] Slope of the trend component of GPP_c, ET_c, and WUE_c decomposed by STL in the Aksu River Basin from 2002 to 2022

3.1.2 GPPc、ETc 和 WUEc 空间变化特征

The maximum annual average decline rate was 0.42 g $\mathrm{C} \cdot \mathrm{mm}^{-1} \cdot \mathrm{a}^{-1}$, while the maximum increase rate reached 0.038 g $\mathrm{C} \cdot \mathrm{mm}^{-1} \cdot \mathrm{a}^{-1}$. The characteristics of the intra-annual variation process in the Aksu River Basin are shown in [Figure 3: see original paper]. The results indicate that the intra-annual variations of GPP and ET in the Aksu River Basin exhibit a typical unimodal pattern, with peaks occurring in July (79.40 g $\mathrm{C} \cdot \mathrm{m}^{-2}$ and 47.66 mm, respectively). During the winter and early spring, these values remain at low levels, with multi-year averages generally below 15 g $\mathrm{C} \cdot \mathrm{m}^{-2}$. From a seasonal perspective, the spatial distribution of these indicators in the Aksu River Basin from 2002 to 2022 consistently shows a significant gradient pattern, characterized by higher values in the northwest and lower values in the southeast. The highest indicators were 542.2 g $\mathrm{C} \cdot \mathrm{m}^{-2}$ for GPP and 249.3 mm for ET, with a corresponding WUE of 1.9 g $\mathrm{C} \cdot \mathrm{mm}^{-1}$. Conversely, the lowest indicators were 307.7 g $\mathrm{C} \cdot \mathrm{m}^{-2}$ and 167.9 mm, with a WUE of 2.2 g $\mathrm{C} \cdot \mathrm{mm}^{-1}$.

Trend analysis reveals that GPP and ET generally exhibit a significant upward trend across the entire basin, with the area of increasing trends accounting for 80.1% of the total region. The most significant increase rates were observed in the northwestern part of the basin. Intra-annually, WUE exhibits a distinct bimodal distribution (Figure 3), with peaks appearing in May and September, while remaining at lower levels (generally below 0.5 g $\mathrm{C} \cdot \mathrm{mm}^{-1}$) during winter and early spring. Although 69.4% of the area showed a significant upward trend in WUE, the magnitude of this increase was relatively small. Regarding long-term temporal trends, 60.3% of the study area showed a downward trend in WUE from 2002 to 2022, with 21.0% of the region reaching a level of significant decline, primarily concentrated in the northwestern part of the basin where the decline rate reached 3.5 g $\mathrm{C} \cdot \mathrm{mm}^{-1} \cdot \mathrm{a}^{-1}$. The variation trend of WUE differs from GPP and ET; specifically, during the crop growing season (May to September), GPP and ET generally increased, whereas WUE exhibited an overall downward trend. This suggests that under the context of climate change, the rate of increase in ET may be faster than that of GPP. This significant spatial differentiation is likely driven by the spatial heterogeneity of hydrothermal conditions, soil characteristics, and agricultural management practices within the basin, reflecting a typical spatial distribution pattern of productivity and water use efficiency in arid oasis agroecosystems.

Fig. 3 [Figure 3: see original paper] Interannual variations of GPPc, ETc, and WUEc in the Aksu River Basin from 2002 to 2022

3.2 基于赫斯特指数的 WUEc 可持续性

Sustainability analysis based on the Hurst exponent indicates that the Aksu River Basin exhibits a general trend toward improvement (including both continuous improvement and future improvement). However, these changes demonstrate significant spatial heterogeneity (Figure 5). While some areas remain stable, the Hurst exponent values across the basin range from 0.18 to 0.81, with a mean value indicating weak persistence.

Spatially, the northwestern part of the basin (Region I) is characterized by a trend toward degradation (including continuous and future degradation). In the central part of the basin (Region II), the proportions of degradation and improvement are roughly equal, each accounting for approximately 50%. In contrast, the southeastern part (Region III) is dominated by improvement, which accounts for 58% to 64% of the area. Slope analysis further reveals that the basin is primarily characterized by improvement (totaling a significant percentage), while the proportion of continuous degradation remains relatively low.

[Figure 4: see original paper] **Fig. 4 Spatial distributions and trends of GPPc, ETc, and WUEc in the Aksu River Basin from 2002 to 2022**

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[Figure 5: see original paper] **Fig. 5 Characteristics of WUEc sustainability in the Aksu River Basin from 2002 to 2022**

3.3.1 气象因子对 WUEc 影响阿克苏河流域

Partial correlation analysis with climatic factors (Figure [FIGURE:N]) reveals that the vegetation index is primarily negatively correlated with temperature ($r = -0.32$) and vapor pressure deficit (VPD, $r = -0.14$). The areas exhibiting negative correlations with these two factors account for 81% and 64% of the study area, respectively. Notably, the negative correlation with temperature displays a spatial pattern that gradually intensifies from south to north. In contrast, the vegetation index is primarily positively correlated with precipitation ($r = 0.17$), with positive correlation areas accounting for 72% of the total area. Negative correlations with precipitation are limited to only 28% of the region, and the correlation coefficients are concentrated between -0.03 and 0.26, suggesting that the inhibitory effect of precipitation is not widespread.

From a regional perspective, the negative correlation between temperature and the vegetation index is particularly prominent in Region II ($r = -0.42$, with a negative correlation area of 91%). In other regions, the proportions of positive and negative correlations are relatively similar, with positive correlations accounting for 56% to 59%. Positive correlations with precipitation remain stable across all regions, ranging from 57% to 71%. Conversely, negative correlations with VPD are dominant in all regions, covering 83% to 94% of the area. Region III stands out as a high-value zone for this effect ($r = -0.36$, with a negative correlation area of 94%). It is noteworthy that areas where the correlation coefficient ranges from -0.30 to -1.00 occupy 38% of the total basin area, indicating that the inhibitory effect of VPD on vegetation is significant and widespread.

3.3.3 多因子协同影响路径通径分析结果表明

There are significant differences in the influence pathways of meteorological and vegetation factors on the Aksu River Basin. Temperature exhibits the strongest overall negative impact, with a total integrated influence coefficient of -0.42. This impact is primarily exerted through direct effects (-0.38) and indirect regulatory mechanisms (-0.04).

Spatial analysis reveals that the negative correlation between precipitation and the target variable is most prominent in Region I, where negative correlations account for 72% of the area. In contrast, Region II displays a more balanced distribution of positive and negative effects, with positive correlations accounting for 51% and 49% of the area, respectively. These findings underscore the complex, spatially heterogeneous response of the hydrological and ecological systems within the basin to shifting climatic drivers.

3.3.2 农田植被因子对 WUEc 影响阿克苏河流域

Partial correlation analysis between WUE_c and cropland vegetation factors (Fig. [Figure 7: see original paper]) indicates a predominantly positive correlation with $NDVI$ and EVI. Specifically, areas exhibiting positive correlations account for 86.4% and 84.2% of the total area, respectively. In contrast, LAI shows a significant negative correlation ($r = -0.43$), with negative correlation areas accounting for 78.5% of the region. Across different sub-regions, positive correlations are primarily driven by the combined effects of $NDVI$ and EVI. While VPD exerts a direct negative influence, its inhibitory effect is partially offset by its role in promoting photosynthesis. Precipitation influences WUE_c through both direct and indirect pathways. Notably, while T exhibits a comprehensive positive effect, VPD shows a weaker net effect due to the presence of opposing internal mechanisms.

In the figure, red sections represent the proportion of positive partial correlation coefficients, while green sections represent the proportion of negative partial correlation coefficients. T denotes air temperature; VPD denotes vapor pressure deficit. The same applies below.

Fig. 6 [Figure 6: see original paper] Spatial distributions of the partial correlation analysis between WUE_c and meteorological factors from 2002 to 2022. $NDVI$ denotes the Normalized Difference Vegetation Index; EVI denotes the Enhanced Vegetation Index; LAI denotes the Leaf Area Index. The same applies below.

Fig. 7 [Figure 7: see original paper] Spatial distributions of the partial correlation analysis between WUE_c and vegetation factors from 2002 to 2022. Zhao Qiu et al.: Spatiotemporal patterns of cropland water use efficiency in the Aksu River Basin. Fig. 8 [Figure 8: see original paper] Path analysis of WUE_c with meteorological factors and cropland vegetation factors.

4 讨论

This paper systematically reveals the spatiotemporal patterns and multi-factor synergistic pathways of the Aksu River Basin. Over the years, the basin's overall trend has shown a significant decline at a rate of 2.1 g $C \cdot mm^{-1}$ ($P < 0.05$), a finding that is fundamentally consistent with existing research results in the southern Xinjiang region (0.02 g $C \cdot mm^{-1}$) [?]. This downward trend primarily stems from the context of climate change, where the significant increase in ET (at a rate of 0.6 g $C \cdot m^{-1}$) is notably higher than the increase in GPP promoted by the CO_2 fertilization effect (with an increase of less than 0.3 $mm \cdot a^{-1}$); the possible mechanism involves an increase in VPD. The intra-annual variation exhibits a typical bimodal characteristic, with peaks appearing in May (the germination period for spring crops) and August (the peak growth period for wheat), which is closely related to crop phenology and seasonal climate changes. Specifically, low temperatures in spring and sustained crop growth in autumn collectively lead to a peak value of 3.0 g $C \cdot mm^{-1}$. These insights provide a new basis for understanding the response mechanisms of agricultural ecosystems in arid regions to climate change.

From the perspective of driving factors and synergistic pathways, the changes in the Aksu River Basin are the result of the combined effects of multiple factors. Temperature and LAI are the dominant factors influencing the basin' s changes, both of which exert a negative impact. LAI is one of the important characteristic parameters reflecting crop growth; on one hand, it can directly influence the resistance to water vapor exchange between the vegetation and the environment, and on the other hand, it affects the light distribution within the crop canopy, thereby indirectly impacting WUE. For the Aksu River Basin, the reason for the negative effect of LAI may be that its increase simultaneously raises agricultural water demand. Given that the basin is located in an arid zone with high surface evaporation, traditional surface canal irrigation exacerbates the evaporation of water from the leaf surface area. This leads to an increase in actual farmland water consumption, causing the rate of photosynthesis in crop leaves to be lower than the rate of transpiration, which in turn leads to a decline in WUE. In addition to LAI as a major influencing factor, precipitation and VPD also play a certain inhibitory or promotional role, either directly or indirectly. For example, precipitation can reduce WUE by lowering crop stomatal conductance, while an increase in VPD can inhibit plant photosynthesis. Existing research indicates that the response of WUE to temperature exhibits a threshold effect, where temperatures that are too high or too low will adversely affect WUE [**?**]. When temperatures are too low, the activity of enzymes involved in plant photosynthesis decreases, reducing the synthesis of GPP; when temperatures are too high, vegetation stomata close, reducing the entry of CO_2 and inhibiting GPP synthesis, while the transpiration rate of leaf stomata increases, leading to a decrease in WUE [**?**]. For the Aksu River Basin, the negative effect produced by temperature primarily stems from the increased diurnal temperature range during the growing season. Overall, moisture is the primary factor leading to low WUE in the Aksu River Basin. By constructing soil and water conservation projects such as ditches and sand-retaining walls, soil erosion can be curbed and surface evaporation inhibited, allowing crops to absorb water more efficiently. These projects also enhance the soil' s infiltration and water storage capacity, further accelerating crop growth and optimizing WUE. Simultaneously, promoting agricultural irrigation methods such as subsurface drip irrigation, micro-sprinkler irrigation, and surge irrigation can reduce water waste and improve water use efficiency.

5 结论

The magnitude of capacity enhancement ($0.6\ \mathrm{g\ C} \cdot \mathrm{m}^{-1}$) was lower than the increase in transpiration rate. On a temporal scale, the Aksu River Basin experienced a significant decline at a rate exceeding $0.3\ \mathrm{mm} \cdot \mathrm{a}^{-1}$, primarily originating from the $0.6\ \mathrm{g\ C} \cdot \mathrm{m}^{-1}$ threshold. Throughout the year, most variables exhibited a unimodal distribution, whereas certain parameters displayed a unique bimodal characteristic, reflecting the coupling effect between phenology and seasonal climate variations.

The peaks observed in specific months reflect the growth cycles of crops. In terms of spatial patterns, the Aksu River Basin generally exhibits a spatial differentiation characterized by higher values in the northwest and lower values in the southeast. In regions above this threshold, trends are increasing, while other areas show a downward trend. This is most significant in the northwestern region (Region 60.3%), where the proportion of continuously degraded area ranges from 58% to 64%, exerting a negative impact. Temperature primarily acts as a major factor by inhibiting growth through the stomatal closure effect. Conversely, other factors influence the system through the transpiration enhancement effect, indicating that agricultural ecosystems in arid zones possess a dual stress mechanism in their response to climate change.

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Temporal and Spatial Variability of Vegetation Water Use Efficiency and Its Response to Precipitation and Temperature

Water Use Efficiency (WUE) is a critical indicator for assessing the coupling between carbon and water cycles in terrestrial ecosystems. Understanding its spatiotemporal dynamics and driving mechanisms is essential for predicting ecosystem responses to climate change, particularly in arid and semi-arid regions.

1. Introduction

The Heihe River Basin, as a typical inland river basin in Northwest China, exhibits significant environmental gradients and diverse ecosystem types. Vegetation in this region is highly sensitive to fluctuations in hydrothermal conditions. Recent studies have highlighted that the spatial distribution of WUE is not only influenced by vegetation types but is also strongly regulated by climatic factors such as precipitation and temperature.

[Figure 1: see original paper]

2. Spatiotemporal Characteristics of WUE

The spatial distribution of WUE in the Heihe River Basin demonstrates a clear gradient, generally increasing from the downstream arid regions to the upstream mountainous areas. This pattern is closely aligned with the distribution of vegetation cover and biomass. In the upper reaches, where precipitation is more abundant and temperatures are lower, forest and alpine meadow ecosystems exhibit higher WUE. Conversely, the lower reaches, characterized by desert-riparian vegetation, show lower and more variable WUE values due to extreme aridity and reliance on groundwater.

Temporally, the WUE of the basin has shown a fluctuating upward trend over the past decades. This increase can be attributed to the combined effects of rising atmospheric CO_2 concentrations, which enhance photosynthesis (the fertilization effect), and improved water management practices in the middle reaches.

3. Response to Precipitation and Temperature

The response of WUE to climatic drivers varies significantly across different climatic zones within the basin. Precipitation is the primary limiting factor for vegetation growth in the middle and lower reaches. In these areas, a positive correlation is often observed between WUE and precipitation, as increased water availability significantly boosts Gross Primary Productivity (GPP) more than it increases Evapotranspiration (ET).

Temperature plays a dual role in regulating WUE. In the high-altitude regions of the upper Heihe River, rising temperatures can extend the growing season and promote carbon sequestration, thereby increasing WUE. However, in the arid lowlands, excessive warming often leads to an increase in the vapor pressure deficit (VPD), which triggers stomatal closure and enhances ET, subsequently resulting in a decline in WUE.

4. Driving Factors and Regional Differences

Recent research, such as the work by Li et

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Analysis of Water Resources Development and Utilization in the Aksu River Basin

1. Introduction

The Aksu River Basin, located in the Xinjiang Uygur Autonomous Region, serves as a critical ecological and economic lifeline for the region. As a primary headwater of the Tarim River, its water resource management is of paramount importance for regional food security, ecological stability, and sustainable development. This study explores the current status of water resource development and utilization within the basin, identifying key challenges and proposing strategic recommendations for optimized management.

2. Overview of Water Resources in the Aksu River Basin

The Aksu River is characterized by its unique hydrological regime, primarily fed by glacier meltwater and seasonal precipitation. The basin’ s water resources are characterized by significant seasonal variability and spatial heterogeneity.

[Figure 1: see original paper]

The total water volume available in the basin is influenced by climatic factors, particularly temperature fluctuations affecting glacial runoff. In recent years, climate change has accelerated glacier retreat, leading to temporary increases in runoff but posing long-term risks to water security. The rational allocation of these resources is essential to balance the competing demands of agriculture, industry, and environmental conservation.

3. Current Status of Development and Utilization

3.1 Agricultural Water Use Agriculture remains the dominant consumer of water in the Aksu River Basin. Large-scale irrigation districts have been established to support the production of cotton, grains, and specialty fruits. While irrigation efficiency has improved through the adoption of drip irrigation and plastic mulch technologies, the overall water consumption remains high, often exceeding the sustainable recharge rates of local aquifers.

3.2 Industrial and Domestic Water Use With the acceleration of urbanization and industrialization in the Aksu region, the demand for industrial and domestic water has seen a steady increase. Although these sectors account for a smaller percentage of total water use compared to agriculture, their requirements for water quality and reliability are significantly higher.

3.3 Ecological Water Requirements Maintaining the ecological health of the Aksu River and its downstream reaches (the Tarim River) is a priority. Ecological water conveyance projects have been implemented to restore riparian vegetation, such as the *Populus euphratica* forests, which are vital for preventing desertification and maintaining biodiversity.

4. Challenges in Water Resource Management

Despite progress in water management, several critical issues persist:

1. **Supply-Demand Imbalance:** The temporal mismatch between peak water demand (summer irrigation) and natural runoff availability

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Spatiotemporal Variation Analysis of Ecosystem Water Use Efficiency in Central Asia and Xinjiang

Introduction

Water Use Efficiency (WUE) is a critical indicator for assessing the coupling between carbon and water cycles within terrestrial ecosystems. It reflects the trade-off between carbon gain through photosynthesis and water loss through evapotranspiration. Understanding the spatiotemporal dynamics of WUE is essential for predicting ecosystem responses to climate change, particularly in arid and semi-arid regions such as Central Asia and Xinjiang, China. These regions are characterized by limited water resources and high sensitivity to environmental fluctuations.

[Figure 1: see original paper]

Methodology and Data Sources

This study utilizes long-term remote sensing datasets and meteorological observations to analyze the trends in ecosystem WUE. The primary metrics employed include Gross Primary Productivity (GPP) and Evapotranspiration (ET), where WUE is defined as the ratio of GPP to ET:

$$WUE = \frac{GPP}{ET}$$

Data processing involved the integration of MODIS-derived products and climate reanalysis data to ensure spatial consistency across the study area. Statistical methods, including Theil-Sen trend analysis and Mann-Kendall tests, were applied to evaluate the significance of observed changes over the study period. Furthermore, we considered structural parameters of the vegetation canopy, such as leaf area index (LAI) and leaf orientation, which significantly influence canopy photosynthesis and transpiration rates [**?**].

Spatiotemporal Dynamics of WUE

The analysis reveals significant spatial heterogeneity in WUE across Central Asia and Xinjiang. Higher WUE values are generally observed in mountainous regions and irrigated agricultural zones, where vegetation density is higher. Conversely, desert margins and degraded grasslands exhibit lower WUE, primarily due to limited biomass production relative to evaporative demand.

Temporally, the region has experienced notable fluctuations in WUE over the past decades. While some areas show an increasing trend in WUE—likely driven by CO_2 fertilization effects and improved irrigation management—other regions face declining efficiency due to intensifying drought conditions and rising temperatures. The relationship between leaf angles, leaf area, and canopy photosynthesis plays a fundamental role in these dynamics, as canopy architecture determines the light interception efficiency and subsequent carbon assimilation [**?**].

Drivers of WUE Variation

The variation in WUE is driven by a complex interplay of climatic and anthropogenic factors. Precipitation remains the dominant limiting factor in these arid ecosystems, influencing both GPP and ET. However, temperature increases have led to higher vapor pressure deficits (VPD), which can

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Vegetation water use efficiency in the arid regions of Northwest China.

Spatiotemporal patterns of cropland water use efficiency in the Aksu River Basin

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Introduction

Water Use Efficiency (WUE) is a critical indicator for assessing the relationship between ecosystem carbon cycles and water cycles. Understanding its spatiotemporal dynamics is essential for managing water resources in arid regions. Previous research has explored these dynamics across various scales. For instance, Xiao (2001) investigated the potential effects of simulated precipitation changes on the evapotranspiration of *Salix psammophylla* seedlings in the Mu Us Sandy Land [?]. More recently, Gao et al. (2023) analyzed the responses of vegetation water use efficiency to meteorological factors across Xinjiang, highlighting the sensitivity of arid ecosystems to climatic shifts [?].

In the context of agricultural sustainability, the Aksu River Basin serves as a vital production base in Northwest China. However, the region faces significant challenges due to water scarcity and the impacts of climate change. This study focuses on the spatiotemporal patterns of cropland WUE within the Aksu River Basin to provide a scientific basis for optimized water allocation and sustainable agricultural development.

Materials and Methods

The study area, the Aksu River Basin, is characterized by an arid continental climate with limited precipitation and high potential evaporation. We utilized remote sensing data and meteorological observations to calculate the Gross Primary Productivity (GPP) and Evapotranspiration (ET). WUE was defined as the ratio of GPP to ET:

$$\mathrm{WUE} = \frac{\mathrm{GPP}}{\mathrm{ET}}$$

Where GPP represents the carbon fixed by the cropland ecosystem through photosynthesis, and ET represents the total water loss through soil evaporation and plant transpiration. Data processing involved the use of machine learning algorithms to interpolate missing values and ensure spatial consistency across the study period.

[Figure 1: see original paper]

Results and Analysis

The analysis reveals distinct seasonal and interannual variations in cropland WUE within the basin. Spatially, WUE exhibits a gradient

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Urumqi 830052, Xinjiang, China) Abstract: Quantitative assessment of the long-term variations in cropland water use efficiency (WUEc) is crucial for optimizing water resource utilization and achieving high yields as well aseffective water-saving in irrigated ag- riculture in arid regions. This research integrates gross primary productivity of crops (GPPc), grop evapotranspira- tion (ETc), WUEc, and meteorological as well as vegetation data in the Aksu River Basin

from 2002 to 2022, a typical arid region, and systematically identifies the spatiotemporal patterns of WUEc and the synergistic effects of multiple driving factorsby applying Sen’s slope, the Mann-Kendall trend test, seasonal and trend decomposi- tion using loess, partial correlation analysis, and path analysis. The results indicate the following: (1) Temporal characteristics: GPPc and ETc in the basin increased significantly at rates of 0.6 g C a−1 and 0.3 mm a−1, re- a − 1. Intraannual dynamics showed a unimodal spectively, while WUEc declined at a rate of 0.02 g C mm − 1 m − 2 pattern for GPPc and ETc (peaking in August), and a bimodal pattern for WUEc (with peaks in April and Octo- ber). (2) Spatial patterns: Regions with declining WUEc accounted for 60.3% of the area under consideration, while those with increasing GPPc and ETc covered 97.1% and 94.8% , respectively, highlighting a widespread phenomenon of “increased production without efficiency gains” in the basin. (3) Driving factor analysis: WUEc was significantly negatively correlated with temperature (T), vapor pressure deficit, and leaf area index (LAI), with the negatively correlated areas corresponding to 77% 89%, and positively correlated with precipitation (Pre), corresponding to 87% of the total area. (4) Path analysis: T and Pre primarily influenced WUEc by regulat- ing GPPc, whereas LAI affected WUEc via ETc. Normalized difference vegetation index and enhanced vegeta- tion index impacted WUEc through the combined regulation of both ETc and GPPc. T and LAI were identified as dominant drivers, suggesting a dual-stress mechanism acting on agroecosystems in arid regions. This study eluci- dates the multi-scale evolution patterns of WUEc in arid regions and its nonlinear driving mechanisms, providing a scientific basis for optimizing agricultural water resource management under climate change.

Keywords: meteorological factors; vegetation factors; crops; water use efficiency; Aksu River Basin