Spatiotemporal Characteristics of Ecosystem Water Use Efficiency and Its Influencing Factors in Yanchi County, Ningxia Postprint

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Date: 2024-06-12T00:00:00+00:00

Abstract

Water Use Efficiency (WUE) is an important indicator for measuring the trade-off relationship between plant photosynthetic carbon fixation and water consumption. Investigating the spatiotemporal variation characteristics of vegetation WUE in the study area is crucial for regional ecological restoration and the rational utilization and development of water resources. This study evaluates the spatiotemporal variation characteristics of vegetation WUE and its main influencing factors in Yanchi County from 2000 to 2019 based on GPP and ET data derived from MODIS. The results show: (1) From 2000 to 2019, ET and GPP in Yanchi County increased significantly at rates of 7.61 $mm \cdot a^{-1}$ and 7.23 $gC \cdot m^{-2} \cdot a^{-1}$, respectively, exhibiting a spatial distribution pattern of high in the northwest and low in the southeast, with strong spatial heterogeneity. (2) Over the past 20 years, vegetation WUE in Yanchi County ranged between 0.80–1.11 $gC \cdot kg^{-1} \cdot H_2O$, with a multi-year mean of 0.91 $gC \cdot kg^{-1} \cdot H_2O$, showing no significant interannual variation; spatially, WUE across the county exhibited strong heterogeneity, with high values mainly distributed in the northeast and low values in the southwest. (3) Over the past 20 years, WUE in Ningxia's Yanchi County showed an increasing trend in 54.70% of the area, mainly distributed in the northeast; 45.30% of the area exhibited a decreasing trend. In the future, the vegetation WUE change trend in 61.48% of Yanchi County's area will have strong persistence in the same direction, while 38.52% of the area will experience a reversal. (4) Across different study periods, WUE for various land use types consistently showed the pattern: forestland > cropland > grassland. (5) At the interannual scale, vegetation WUE showed a significant positive correlation with GPP, but no correlation with ET; changes in GPP were mainly significantly positively correlated with ET, NDVI, and precipitation. This indicates that vegetation restoration in Yanchi County has enhanced vegetation productivity while also intensifying regional water consumption, providing a scientific basis for future ecological vegetation reconstruction and rational development of water resources in Yanchi.

Full Text

Temporal and Spatial Characteristics of Ecosystem Water Use Efficiency and Its Influencing Factors in Yanchi County, Ningxia

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Abstract

Water use efficiency (WUE) is a critical indicator for evaluating the trade-off between photosynthetic carbon fixation and water consumption in ecosystems. Understanding the spatiotemporal variation characteristics of regional vegetation WUE is essential for ecological restoration and rational water resource utilization. Based on MODIS data from 2000 to 2019, this study analyzed the spatiotemporal variation patterns of vegetation WUE and their main driving factors in Yanchi County, Ningxia. The results showed that: (1) Both evapotranspiration (ET) and gross primary productivity (GPP) exhibited significant increasing trends from 2000 to 2019 ($P < 0.01$), with rates of 7.61 $mm \cdot a^{-1}$ and 7.23 $g\ C \cdot m^{-2} \cdot a^{-1}$, respectively. Spatially, 61.48% of the county's vegetation WUE showed a significant increase, while 54.70% of the area exhibited a significant decrease. (2) The vegetation WUE in Yanchi County ranged from 0.80 to 1.11 $g\ C \cdot kg^{-1}\ H_2O$, with a multi-year average of 0.91 $g\ C \cdot kg^{-1}\ H_2O$. The spatial distribution showed strong heterogeneity, with high values mainly in the northeast and low values in the southwest. (3) From 2000 to 2019, 54.70% of the region showed an increasing trend in WUE, primarily distributed in the northeast, while 45.30% showed a decreasing trend. The Hurst index analysis revealed that 61.48% of pixels had $H > 0.5$, indicating strong persistence in WUE trends, while 38.52% may experience trend reversal in the future. (4) Across different study periods, WUE for various land use types followed the pattern: forestland > cropland > grassland. (5) WUE was significantly positively correlated with GPP and precipitation ($P < 0.05$), but not with temperature. This indicates

that ecological restoration in Yanchi County has enhanced vegetation productivity while intensifying regional water consumption, providing a scientific basis for future ecological revegetation and water resource development.

Keywords: water use efficiency; gross primary productivity; evapotranspiration; desert steppe; ecological restoration; Ningxia

1. Data and Methods

1.1 Study Area Yanchi County is located in eastern Ningxia (37°04 –38°10 N, 106°30 –107°47 E) at an elevation of 1295–1951 m. It borders the Mu Us Desert to the north and connects to the Loess Plateau in the southeast, with terrain sloping from high in the south to low in the north. The region transitions from semi-arid to arid climate, characterized by a typical temperate continental climate. The average annual temperature is 8.34°C, with precipitation concentrated in June–September. Annual precipitation averages 296.96 mm. Vegetation transitions from dry steppe to desert steppe, dominated by psammophytic herbs and shrubs. Major herbaceous species include *Lespedeza davurica*, *Stipa breviflora*, and *Leymus secalinus*, while shrubs are mainly *Salix psammophila* and *Caragana intermedia*. Since the late 1990s, ecological restoration projects have been implemented, significantly increasing vegetation coverage and altering vegetation composition.

1.2 Data Sources This study utilized MODIS products including MOD17A2H (GPP) and MOD16A2 (ET) from NASA (https://ladsweb.modaps.eosdis.nasa.gov) for 2000–2019, with a spatial resolution of 500 m. Data preprocessing included format conversion, reprojection, and mosaicking. Land use data were obtained from the Chinese Academy of Sciences Resource and Environmental Science Data Center (http://www.resdc.cn) for 2000, 2005, 2010, and 2015, with 30 m resolution. Land use types included cropland (dryland and paddy fields), forestland (woodland, sparse woodland, shrubland, and other forestland), and grassland (low, medium, and high coverage grassland).

1.3 Research Methods 1.3.1 WUE Calculation

WUE was calculated as the ratio of GPP to ET:

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

where WUE is water use efficiency ($g\ C \cdot kg^{-1}\ H_2O$), GPP is gross primary productivity ($g\ C \cdot m^{-2}$), and ET is evapotranspiration ($kg\ H_2O \cdot m^{-2}$).

1.3.2 Trend Analysis

Theil-Sen median trend analysis was used to evaluate temporal trends in WUE:

$$k = \text{median}\left(\frac{X_j - X_i}{j - i}\right), \quad \forall 1 < i < j < n$$

where k is the trend slope, n is the study period length, and X represents annual WUE values. The Mann-Kendall test was used for significance testing at P = 0.05. A positive k indicates an increasing trend, while negative k indicates a decreasing trend.

1.3.3 Rescaled Range Analysis and Hurst Index

Rescaled range analysis (R/S) was applied to calculate the Hurst index (H). For a time series (t), the method involves creating mean sequences, cumulative deviations, range (R), and standard deviation (S). If $R/S \quad \tau$, the series exhibits Hurst phenomenon. The Hurst index has three forms: (1) When $0.5 < H < 1$, the series is persistent, meaning future trends follow past trends, with stronger persistence as H approaches 1; (2) When $H = 0.5$, the series is random; (3) When $0 < H < 0.5$, the series is anti-persistent, with future trends opposite to past trends, and stronger anti-persistence as H approaches 0.

2. Results

2.1 Spatiotemporal Characteristics of ET and GPP 2.1.1 Temporal Variation of ET and GPP

From 2000 to 2019, ET in Yanchi County showed a significant increasing trend ($P < 0.01$) at a rate of 7.61 mm $\cdot$ a^{-1}, with strong interannual variability. Annual ET ranged from 153.39 to 325.71 mm, averaging 255.36 mm. The lowest value (153.39 mm) occurred in 2001, 101.65 mm below the multi-year average, while the highest (325.71 mm) occurred in 2016, 70.35 mm above average. This increase is attributed to large-scale implementation of the Grain-for-Green Program and grazing prohibition policies, which improved vegetation coverage in desert steppe areas.

GPP also showed a significant increasing trend ($P < 0.01$) at 7.23 g $C \cdot m^{-2} \cdot a^{-1}$, with large interannual fluctuations. Annual GPP ranged from 126.35 to 336.67 g $C \cdot m^{-2}$, averaging 233.38 g $C \cdot m^{-2}$. The lowest value (126.35 g $C \cdot m^{-2}$) occurred in 2001, 107.03 g $C \cdot m^{-2}$ below average, while the highest (336.69 g $C \cdot m^{-2}$) occurred in 2018, 103.31 g $C \cdot m^{-2}$ above average. The relatively stable trend from 2015–2019 was mainly related to extreme meteorological drought events, which reduced ecosystem productivity and ET. Post-drought recovery was observed following water replenishment.

2.1.2 Spatial Distribution of ET and GPP

ET showed strong spatial heterogeneity, with a northwest-low, southeast-high pattern consistent with precipitation and vegetation coverage distribution. County-wide ET ranged from 210.77 to 404.44 mm, averaging 255.16 mm. High ET values were mainly distributed in the loess hilly region in the south, where precipitation and vegetation coverage are relatively high. Local high values also appeared as patches in agricultural irrigation and ecological restoration areas around Hui'anbao Town. Low ET values occurred in the northwestern desert steppe region with low vegetation coverage and precipitation.

GPP also exhibited strong spatial heterogeneity, ranging from 90.39 to 550.67 $g\ C \cdot m^{-2}$, with an average of 232.60 $g\ C \cdot m^{-2}$. High GPP values were mainly in the northeast and southeast, particularly in Fengjigou and Hui'anbao where irrigation agriculture and ecological restoration projects have promoted good crop growth. Low GPP values were distributed in the northwest and southwest, especially in southern Gaoshawo Town and northern Wanglejing Town.

2.2 Spatiotemporal Distribution of WUE From 2000 to 2019, ecosystem WUE in Yanchi County ranged from 0.80 to 1.11 $g\ C \cdot kg^{-1}\ H_2O$, with a multi-year average of 0.91 $g\ C \cdot kg^{-1}\ H_2O$. The increasing rate was 0.0013 $g\ C \cdot kg^{-1}\ H_2O \cdot a^{-1}$, which was not significant ($P > 0.05$). Although both ET and GPP increased significantly, their similar growth rates maintained WUE within a relatively stable range. WUE showed large interannual fluctuations, particularly during extreme drought events (e.g., 2001, 2015, 2017) when both productivity and ET declined, resulting in low WUE values. Post-drought recovery periods showed high WUE values.

Spatially, WUE exhibited strong heterogeneity with a northeast-high, southwest-low pattern. The spatial range was 0.38–1.45 $g\ C \cdot kg^{-1}\ H_2O$, averaging 0.91 $g\ C \cdot kg^{-1}\ H_2O$. High WUE values were mainly in Huamachi Town in the northeast, while low values were in southern and eastern regions.

2.3 Trends in WUE From 2000 to 2019, 54.70% of Yanchi County showed increasing WUE trends, with only 8.85% being statistically significant, primarily in northeastern Huamachi Town, eastern Qingshan, and parts of Wanglejing and Hui'anbao. Decreasing trends occupied 45.30% of the area, with 1.43% being significant.

The Hurst index ranged from 0.27 to 0.86, averaging 0.58. Pixels with $H > 0.5$ accounted for 61.48% of the total, indicating that most areas will maintain the same trend direction in the future. Only 38.52% may experience trend reversal.

2.4 WUE Variations Across Land Use Types WUE varied significantly among land use types (excluding paddy fields) over time. Forestland showed the highest WUE, followed by cropland and grassland. All land use types showed low WUE during persistent drought periods (2015–2017) and increased values post-drought, influenced by increased precipitation. Under combined climate change and human activity impacts, different land use types showed distinct temporal patterns.

Overlay analysis of WUE trend slopes and Hurst indices revealed four change patterns: persistent increase (33.49%), increase-to-decrease reversal (27.99%), decrease-to-increase reversal (17.30%), and persistent decrease (21.22%). This indicates that most currently increasing areas will continue to increase, while about 17.30% will reverse. Areas with persistent increases were mainly in Dashuikeng and Huamachi towns, while persistent decreases were in southern Mahuangshan and southwestern Hui'anbao.

2.5 Analysis of Influencing Factors 2.5.1 Relationship Between WUE, ET, and GPP

At the interannual scale, WUE was significantly positively correlated with GPP ($P < 0.05$) but not with ET. However, GPP was significantly positively correlated with ET ($P < 0.01$), indicating that increased vegetation productivity significantly enhances ecosystem water consumption. The correlation between WUE and ET was weak ($R^2 = 0.08$, $P > 0.05$), suggesting that WUE fluctuations were primarily driven by GPP variations.

2.5.2 Impacts of Climate and Vegetation Factors

WUE showed no significant correlation with temperature or precipitation individually ($P > 0.05$). However, both ET and GPP were significantly positively correlated with precipitation ($P < 0.05$) but not with temperature. From 2000 to 2019, precipitation increased significantly ($P < 0.05$) while temperature showed no significant trend. This indicates that WUE changes were indirectly driven through precipitation and vegetation impacts on ET and GPP. NDVI also increased significantly, reflecting vegetation restoration effects.

3. Discussion

Vegetation in Yanchi County has changed significantly since 2000 due to ecological restoration projects. These changes have altered regional water characteristics and produced feedback effects on ecosystem sustainability. Ecosystem WUE is regulated by both internal vegetation functional traits and external environmental conditions. Understanding WUE changes requires examining both internal factors and the impacts of climate change and human activities.

This study found that both ET and GPP increased significantly, indicating that ecological restoration has enhanced vegetation coverage and productivity while intensifying water consumption. According to stomatal conductance theory, plants regulate water loss while assimilating carbon through stomatal opening and closing, thereby improving WUE. The significant positive correlation between WUE and GPP, but not between WUE and ET, suggests that GPP variation is the primary driver of WUE changes. This aligns with findings from the Loess Plateau where WUE increases were attributed to vegetation growth.

However, the significant positive correlation between GPP and ET indicates that vegetation restoration increases water consumption. If this trend continues, soil water depletion may limit plant growth and threaten ecosystem stability. While

WUE was not directly correlated with temperature, precipitation showed significant positive correlations with both ET and GPP. The substantial interannual variability in precipitation in this arid/semi-arid region significantly impacts WUE, with persistent drought events causing vegetation stress and reducing WUE. Therefore, ecological restoration must balance vegetation water demand with water supply to ensure sustainable development.

4. Conclusions

Based on MODIS products, this study quantitatively analyzed the spatiotemporal characteristics of vegetation WUE in Yanchi County from 2000 to 2019. The main conclusions are:

1) Both ET and GPP increased significantly at rates of 7.61 $mm \cdot a^{-1}$ and 7.23 $g\ C \cdot m^{-2} \cdot a^{-1}$, respectively ($P < 0.01$). WUE ranged from 0.80 to 1.11 $g\ C \cdot kg^{-1}\ H_2O$, averaging 0.91 $g\ C \cdot kg^{-1}\ H_2O$, with a non-significant increasing trend.

2) Spatially, vegetation WUE showed strong heterogeneity, with high values in the northeast and low values in the southwest.

3) From 2000 to 2019, 54.70% of the area showed increasing WUE trends while 45.30% showed decreasing trends. Most areas (61.48%) will maintain the same trend direction in the future, with only 38.52% likely to reverse.

4) At the interannual scale, WUE changes were significantly correlated with GPP and precipitation, indicating that ecological restoration has enhanced vegetation productivity while intensifying regional water consumption.

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Note: Figure translations are in progress. See original paper for figures.