

Response of Water Use Efficiency to Climate Change in Five Central Asian Countries, 2000-2018: Postprint

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Abstract

Water use efficiency (WUE) is a commonly used metric for investigating the coupling of terrestrial carbon and water cycles. Using MODIS gross primary productivity (GPP) and evapotranspiration (ET) data, we examined the spatiotemporal variation patterns of WUE in Central Asia and its dynamic responses to climate factors and drought through Slope trend analysis and sensitivity analysis. The results indicate: (1) During 2000-2018, the annual mean WUE in Central Asia increased with habitat moisture (the pattern was reversed during the growing season), with wetlands exhibiting the highest WUE ($1.820 \pm 0.10 \text{ gC} \cdot \text{mm}^{-1} \cdot \text{m}^{-2}$) and shrubland the lowest ($1.330 \pm 0.18 \text{ gC} \cdot \text{mm}^{-1} \cdot \text{m}^{-2}$). (2) WUE in Central Asia exhibited a slight decreasing trend at a rate of $0.016 \text{ gC} \cdot \text{mm}^{-1} \cdot \text{m}^{-2}$ per year, with the area of significant decline exceeding that of increase. The sensitivity of WUE to both annual precipitation and temperature displayed threshold effects, where areas of positive sensitivity exceeded those of negative sensitivity. The precipitation sensitivity threshold ranged between 250-300 mm (lower point) and 500-550 mm (higher point), while the temperature threshold ranged between 3-6 °C (higher point) and 9-12 °C (lower point). Furthermore, NDV (the sensitivity coefficient of IWUE to NDVI) was positively correlated with precipitation changes and negatively correlated with temperature changes. (3) Through correlation analysis between WUE and the Standardized Precipitation Evapotranspiration Index (SPEI), we found that the influence of drought severity on WUE decreased in the order of shrubland, cropland, forest, grassland, and wetland, and that WUE across different vegetation types increased with intensifying drought severity.

Full Text

Response of Water Use Efficiency to Climate Change in Five Central Asian Countries from 2000 to 2018

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Abstract: Water use efficiency (WUE) is a commonly used metric for studying the coupling between terrestrial carbon and water cycles. Using MODIS gross primary productivity (GPP) and evapotranspiration (ET) data from 2000 to 2018, we analyzed the spatiotemporal variation patterns of WUE in Central Asia and its dynamic responses to climatic factors and drought through slope trend analysis and sensitivity analysis. The results show that: (1) From 2000 to 2018, the mean annual WUE increased with habitat humidity (with the opposite pattern during the growing season), reaching its maximum in wetlands ($1.82 \pm 0.10 \text{ gC} \cdot \text{mm}^{-1} \cdot \text{m}^{-2}$) and minimum in shrublands ($1.33 \pm 0.18 \text{ gC} \cdot \text{mm}^{-1} \cdot \text{m}^{-2}$). Overall, WUE exhibited a slight decreasing trend at a rate of $0.016 \text{ gC} \cdot \text{mm}^{-1} \cdot \text{m}^{-2}$ per year, with significantly declining areas exceeding significantly increasing areas. (2) The sensitivity of WUE to annual precipitation and temperature both showed larger positive-value regions than negative-value regions, with evident threshold effects. The precipitation sensitivity threshold ranged between 250–300 mm (low point) and 500–550 mm (high point), while the temperature threshold ranged between 3–6°C (low point) and 9–12°C (high point). The sensitivity coefficient to NDVI (NDVI) was positively correlated with precipitation changes but negatively correlated with temperature changes. (3) WUE responses to drought varied by vegetation type, decreasing in the order of shrubland > cropland > forest > grassland > wetland. Under different vegetation types, WUE increased with drought severity. The correlation coefficients between WUE and SPEI were 0.83, 0.81, and 0.70 for wooded grassland, mixed forest, and open shrubland, respectively, while they were -0.35, -0.22, and 0.02 for deciduous needleleaf forest, permanent wetland, and grassland, respectively.

Key words: Central Asia; sensitivity; climate change; water use efficiency; vegetation types

1.2 Data Sources

1.2.1 Meteorological Data The meteorological dataset was obtained from the Climatic Research Unit (CRU) at the University of East Anglia, covering

the period 2000–2018 with a spatial resolution of $0.5^\circ \times 0.5^\circ$. The data include monthly precipitation, mean temperature, and other variables. After quality control and processing, these data were used to calculate the Standardized Precipitation Evapotranspiration Index (SPEI) and analyze climate trends across Central Asia.

1.2.2 GPP, ET, NDVI, and Land Cover Data GPP data were derived from the MOD17A2 product, ET from MOD16A2, and NDVI from MOD13, all part of the MODIS Terra satellite suite. These products provide 8-day temporal resolution and 500 m spatial resolution. Land cover data were obtained from the MCD12Q1 product (500 m resolution) using the International Geosphere-Biosphere Programme (IGBP) classification scheme. The study area comprises five Central Asian countries: Kazakhstan, Kyrgyzstan, Tajikistan, Turkmenistan, and Uzbekistan, covering $35^\circ 07' - 55^\circ 26' \text{ N}$ and $46^\circ 29' - 87^\circ 18' \text{ E}$. The dominant land cover types are grassland (85.73%), barren or sparsely vegetated (6.26%), and cropland (4.74%).

1.3 Methods

1.3.1 WUE Calculation WUE was calculated as the ratio of GPP to ET:

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

where GPP is in $\text{g C} \cdot \text{m}^{-2}$ and ET is in mm, yielding WUE units of $\text{g C} \cdot \text{mm}^{-1} \cdot \text{m}^{-2}$. Annual WUE values were computed from the 8-day composite data for each pixel.

1.3.2 Trend Analysis Temporal trends in WUE were analyzed using linear regression:

$$\text{Slope} = \frac{n \sum_{j=1}^n j \cdot WUE_j - \sum_{j=1}^n j \sum_{j=1}^n WUE_j}{n \sum_{j=1}^n j^2 - (\sum_{j=1}^n j)^2}$$

where n is the number of years (19) and WUE_j is the WUE value in year j . The significance of trends was tested at $P < 0.05$ and $P < 0.01$ levels. The spatial distribution of trends is shown in [Figure 4: see original paper].

1.3.3 Sensitivity Coefficient Sensitivity of WUE to climate factors was calculated as:

$$\varepsilon = \frac{\partial WUE}{\partial X} \times \frac{\bar{X}}{\overline{WUE}} \times 100\%$$

where X represents precipitation, temperature, or NDVI, and \bar{X} and \overline{WUE} are their mean values. The magnitude of change was classified according to .

1.3.4 Pearson Correlation Coefficient Pearson correlation analysis was conducted between WUE and SPEI to assess drought responses. Correlations were calculated for different vegetation types and drought stages.

2 Results and Analysis

2.1 Spatiotemporal Variation Characteristics and Trends of WUE in Central Asia From 2000 to 2018, mean annual GPP in Central Asia was $58.35 \text{ g C} \cdot \text{m}^{-2}$, ET was $40 \text{ mm} \cdot \text{m}^{-2}$, and WUE was $1.82 \pm 0.10 \text{ g C} \cdot \text{mm}^{-1} \cdot \text{m}^{-2}$. WUE showed a slight decreasing trend of $0.016 \text{ g C} \cdot \text{mm}^{-1} \cdot \text{m}^{-2}$ per year, with 56.05% of the region exhibiting positive sensitivity to precipitation and 43.95% showing negative sensitivity. The spatial distribution revealed that high WUE values ($>1.8 \text{ g C} \cdot \text{mm}^{-1} \cdot \text{m}^{-2}$) were concentrated in the northern grasslands and mountainous areas, while low values ($<1.3 \text{ g C} \cdot \text{mm}^{-1} \cdot \text{m}^{-2}$) occurred in the southern deserts. Significant decreasing trends covered 31.7% of the region, primarily in Turkmenistan and Uzbekistan, whereas significant increasing trends occupied only 18.2%, mainly in northern Kazakhstan [FIGURE:2-4].

2.2 Sensitivity Analysis of WUE to Precipitation, Temperature, and NDVI WUE sensitivity to precipitation (ε_{Pre}) was positive across 66.93% of Central Asia, with the highest sensitivity (0.75 ± 0.58) occurring in the 250–300 mm precipitation zone. Temperature demonstrated a positive correlation with precipitation ($r = 0.71$, $P < 0.01$) and a negative correlation with temperature ($r = -0.49$, $P < 0.01$). Threshold effects were evident, with precipitation sensitivity transitioning at 250–300 mm and 500–550 mm, and temperature sensitivity shifting at 3–6°C and 9–12°C [FIGURE:5, TABLE:2].

2.3 Response of WUE to Drought Under Different Vegetation Types WUE responses to drought varied significantly among vegetation types. Wooded grassland, mixed forest, and open shrubland showed strong positive correlations with SPEI ($r = 0.83$, 0.81 , and 0.70 , respectively), indicating that WUE in these ecosystems increases under wetter conditions. Conversely, deciduous needleleaf forest, permanent wetland, and grassland exhibited weak or negative correlations ($r = -0.35$, -0.22 , and 0.02 , respectively). The sensitivity ranking to drought severity was: shrubland $>$ cropland $>$ forest $>$ grassland $>$ wetland. Notably, WUE increased with drought severity across all vegetation types, with the rate of increase being highest in shrublands ($0.21 \text{ g C} \cdot \text{mm}^{-1} \cdot \text{m}^{-2}$ per SPEI unit) and lowest in wetlands ($0.03 \text{ g C} \cdot \text{mm}^{-1} \cdot \text{m}^{-2}$ per SPEI unit) [FIGURE:6, TABLE:3].

3 Discussion

The observed WUE values in Central Asia (1.33 – $1.82 \text{ g C} \cdot \text{mm}^{-1} \cdot \text{m}^{-2}$) are consistent with global terrestrial ecosystem estimates of 0 – $5 \text{ g C} \cdot \text{mm}^{-1} \cdot \text{m}^{-2}$. The slight decreasing trend in WUE contrasts with patterns observed in some other

arid regions, likely reflecting unique climate-vegetation interactions in Central Asia. The threshold effects at 250–300 mm and 500–550 mm precipitation correspond to ecological transitions between desert, steppe, and forest ecosystems. Similarly, the temperature thresholds of 3–6°C and 9–12°C align with critical phenological phases in regional vegetation. The positive correlation between ε_{NDVI} and precipitation suggests that vegetation greening enhances WUE in water-limited environments, while the negative correlation with temperature indicates thermal stress effects. The differential drought responses among vegetation types highlight the importance of plant functional traits, with deep-rooted shrubs showing greater sensitivity than shallow-rooted grasses. These findings underscore that WUE is not solely determined by climate but is strongly mediated by vegetation structure and physiological adaptations.

4 Conclusions

- (1) From 2000 to 2018, Central Asia's mean annual WUE exhibited a slight decreasing trend at $0.016 \text{ g C} \cdot \text{mm}^{-1} \cdot \text{m}^{-2}$ per year, with significantly declining areas exceeding significantly increasing areas. Mean WUE ranged from $1.33 \pm 0.18 \text{ gC} \cdot \text{mm}^{-1} \cdot \text{m}^{-2}$ in shrublands to $1.82 \pm 0.10 \text{ gC} \cdot \text{mm}^{-1} \cdot \text{m}^{-2}$ in wetlands.
- (2) WUE sensitivity to precipitation and temperature displayed threshold effects, with critical transitions at 250–300 mm and 500–550 mm for precipitation, and 3–6°C and 9–12°C for temperature. The NDVI sensitivity coefficient was positively correlated with precipitation but negatively correlated with temperature.
- (3) Drought impacts on WUE varied by vegetation type, decreasing in sensitivity from shrubland to cropland, forest, grassland, and wetland. WUE increased with drought severity across all vegetation types, with correlation coefficients to SPEI ranging from -0.35 to 0.83 depending on vegetation type.

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