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Spatial distribution and drivers of water use efficiency in global basins, 2002-2021

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Abstract:

Water Use Efficiency (WUE) is an important ecological indicator for evaluating the productivity of ecosystems in utilizing water resources, providing a scientific basis for understanding the dynamic balance between water availability and vegetation productivity. Against the backdrop of climate change and increasing human demand for water, the monitoring of WUE on a global scale has become increasingly significant. By integrating remote sensing data, such as Gross Primary Productivity (GPP) and Evapotranspiration (ET), with spatiotemporal analyses at the basin scale, researchers can uncover regional variations in ecosystem functionality and develop strategies to address water resource allocation challenges. In addition, mapping WUE at the basin scale provides a clear and intuitive visualization of regional productivity disparities while offering timely and spatially targeted management tools. These maps, when combined with data on land use, climate change, and ecological conservation, can promote the efficient utilization of water resources and enhance the long-term stability of ecosystems. This multidimensional and multiscale analysis reveals regional characteristics under the context of global change and contributes to advancing ecological sustainability.

This study utilized MODIS-derived GPP and ET datasets to estimate the WUE of global basins from 2002 to 2021, providing a detailed analysis of their spatiotemporal dynamics. To investigate the factors driving WUE variability, we employed the random forest algorithm, a machine learning approach, to systematically assess the relative contributions of key biotic and abiotic variables. The variables considered in this analysis included land surface temperature (LST), precipitation (Prcp), leaf area index (LAI), normalized difference vegetation index (NDVI), enhanced vegetation index (EVI), vapor pressure deficit (VPD), elevation (EL), and slope. By quantifying the differential influences of these variables, this study not only established an importance ranking of WUE drivers but also revealed significant spatial heterogeneity in the mechanisms governing WUE across diverse hydrological regions. Integrating remote sensing data with advanced machine learning techniques provides a robust analytical framework for disentangling the complex interactions among vegetation, climate, and topography, thereby offering actionable insights to inform region-specific water resource management strategies and ecological planning.

To reveal the spatial distribution characteristics of WUE at the global basin scale, thematic maps were generated using the ArcGIS Pro platform. Basin boundaries were delineated based on the HydroBASINS dataset, and mean annual WUE values were mapped accordingly. A stretched renderer was employed for visualization, with the color gradient designed in accordance with principles of perceptual uniformity to ensure that variations in value were clearly and accurately represented. Additionally, the number of basins corresponding to each WUE classification level was overlaid to highlight regional disparities and value distributions.To further explore the spatial patterns of WUE, the mean WUE value was calculated across all pixels along each longitudinal and latitudinal line, respectively. Line charts were produced to illustrate the longitudinal and latitudinal gradients of WUE, revealing large-scale spatial trends and ecosystem responses across varying climatic and geographic zones.

The mean distribution of global WUE spans from 0 to 3.5 g C kg^{-1} H_2O. Higher WUE values are predominantly concentrated in regions such as the southern Sahara Desert, the area surrounding the Kalahari Desert, and the Indus River basin. These elevated WUE values may be explained by vegetation and ecosystem traits that exhibit higher WUE under arid climate conditions. In contrast, relatively lower WUE values are predominantly observed in basins located in high-latitude and high-altitude regions, likely due to factors such as low temperatures, sparse vegetation cover, and limited water availability in these areas. Over the past two decades, global WUE has ranged from 0.03 to 3.22 g C kg^{-1} H_2O, with a mean of 1.47 g C kg^{-1} H_2O. Notably, certain basins in the southern Sahara Desert exhibit extreme high values, largely due to insufficient data availability and the combination of higher GPP and lower ET, resulting in higher WUE. Fifty percent of the basins have WUE values below 1.50 g C kg^{-1} H_2O, suggesting low WUE across most basins. The first quartile is 1.03 g C kg^{-1} H_2O, and the third quartile is 1.86 g C kg^{-1} H_2O, indicating an asymmetric distribution

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of WUE values, with some basins exhibiting WUE significantly higher than the overall mean. These disparities can be attributed to variations in climatic conditions, land use patterns, and ecosystem adaptation strategies across different regions.

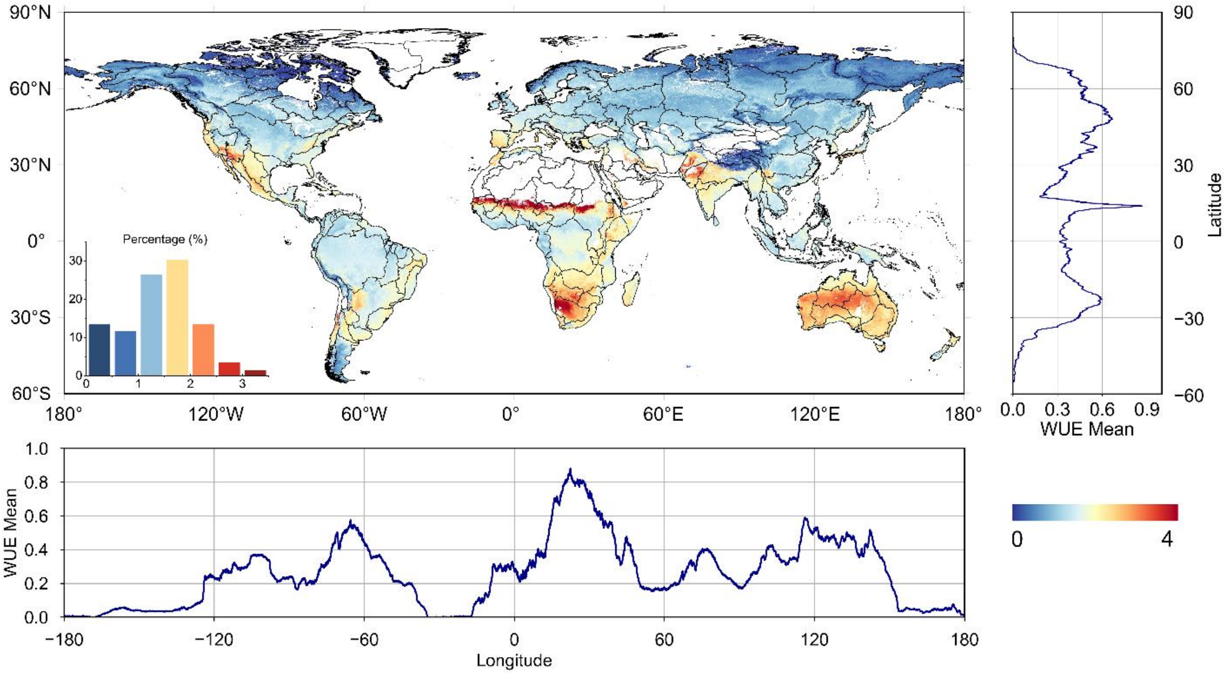

Figure 1. Spatial distribution of global WUE and frequency distribution of WUE in basins.

The importance ranking of influencing factors was analyzed across 173 basins, each spanning over 1.0×105 km2. These variations exhibited significant differences in both magnitude and direction, largely shaped by the geographical diversity of the basins. The ranking of importance among factors influencing WUE identified LAI as the most influential driver in 59 basins, accounting for 34.10% of the total. LAI's dominance underscores its pivotal role in regulating water and carbon fluxes, given its direct influence on transpiration and photosynthesis processes. The second most critical factor was the NDVI, prominent in 33 basins (19.08%). NDVI, reflecting vegetation health and density, highlights the importance of vegetation dynamics in determining basin-specific WUE. VPD ranked third, shaping WUE in 22 basins (12.72%). This emphasizes the role of atmospheric demand for moisture in driving variations, particularly in regions with high evaporative stress. Other notable contributors included LST in 18 basins (10.40%), which influences soil moisture availability and evaporation rates, and EL and EVI, each critical in 15 basins (8.67%). These factors collectively point to the interplay between vegetation vigor, thermal conditions, and altitudinal gradients in modulating WUE. Additionally, Prcp played a significant role in 9 basins (5.20%), reaffirming its direct contribution to water availability, while slope, albeit less frequent, emerged as a determinant in 2 basins (1.16%), likely reflecting its influence on runoff and soil-water retention. The results indicate that vegetation metrics (LAI, NDVI, and EVI) and climate variables (VPD, LST, and precipitation) collectively dominate WUE dynamics, emphasizing their intertwined effects. Notably, LAI's consistent leadership across basins illustrates its overarching importance in regions with varied vegetation and hydrological settings. Meanwhile, the influence of topographic features such as elevation and slope suggests the complexity of localized hydrological and land-atmosphere interactions. These findings highlight how local climate, land cover, and topographical variations shape the spatial heterogeneity of WUE, offering critical insights into basin-specific water-use strategies.

In conclusion, this study presents a comprehensive evaluation of global WUE patterns and the environmental factors influencing its variability, providing a robust analytical framework to elucidate the intricate interactions among climate, vegetation, and topography across diverse hydrological regions. The findings highlight the pivotal role of integrating multiple environmental variables, including climate conditions, land cover characteristics, and topographical features, in accurately assessing WUE at the basin scale. This approach advances the understanding of WUE dynamics and offers critical insights to support region-specific water resource management and sustainable ecological planning under changing environmental conditions.

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