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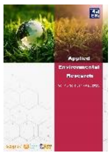

Research Article

Spatial and Temporal Dynamics of Water Use Efficiency and Climate Influence in The Central Highlands of Vietnam via Satellite Time Series

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Abstract

This study investigates the spatial and temporal patterns of water use efficiency (WUE) anomalies across the Central Highlands of Vietnam from 2001–2024 via MODIS time series data, with a focus on seasonal differences and climatic drivers. The results revealed pronounced interannual and spatial variability in the WUE, with significant improvements observed during 2004, 2015, and 2021–2024 and substantial declines during 2005–2008, 2010–2013, and 2016–2017, which coincided with major drought events in the region. Seasonal analysis indicated that WUE was lower during the early dry season and peaked during the postmonsoon months (October–November), reflecting the interplay between water availability and vegetation productivity. Land cover-specific trends revealed greater variability in rainfed croplands than in forests. Additionally, spatial trend analysis revealed widespread positive WUE trends during the dry and rainy seasons, accounting for nearly 35% of the study area. Correlation analysis demonstrated that WUE was more sensitive to climate variables during the dry season, particularly showing positive associations with solar radiation and negative associations with soil moisture and rainfall. During the rainy season, the WUE responses were weaker and more stable. These findings highlight the vulnerability of WUE to climatic variability during the dry season and emphasize the importance of adaptive land and water management strategies to increase ecosystem resilience under future climate change scenarios.

ARTICLE HISTORY

Received: 27 Apr. 2025
Accepted: 30 Jul. 2025
Published: 1 Aug. 2025

KEYWORDS

WUE;
Climate variability;
Vietnam;
Ecosystem response;
Remote sensing

Introduction

Water use efficiency (WUE) is a key ecological indicator that reflects the balance between carbon assimilation through photosynthesis and water loss via evapotranspiration [1–3]. As such, it serves as a critical metric for assessing how effectively ecosystems use available water to support biomass production. In the face of increasing climate variability, land degradation, and growing pressure on freshwater resources, monitoring the WUE provides valuable insights into ecosystem resilience and functionality. During water-limited periods, the WUE becomes a sensitive indicator of vegetation stress and adaptive responses [4–5]. For example, plants often reduce transpiration to conserve moisture, which can lead to shifts in WUE that reveal both physiological adjustments and productivity losses. Therefore, examining the spatial and temporal dynamics of WUE enhances our understanding of vegetation–climate interactions and plays an important role in drought assessment and early warning systems.

The WUE has historically been measured through field-based methods that involve direct observations of plant gas exchange, biomass production, and water consumption [6–8]. While these approaches provide high accuracy and valuable insights into plant physiological processes, they are often limited in spatial coverage, labor intensive, and costly to maintain over large areas and long periods. In recent years, remote sensing has

https://doi.org/10.35762/AER.2025028

provided an alternative opportunity to overcome these limitations [3, 8]. Among the available Earth observation platforms, the Moderate Resolution Imaging Spectro-radiometer (MODIS) plays a key role in advancing WUE research [2, 9]. MODIS provides high temporal frequency and moderate spatial resolution data that support the generation of a wide array of biophysical products, including gross primary productivity (GPP) [10–11] and evapotranspiration (ET) [12–13]. Integrating MODIS-derived GPP and ET makes it possible to estimate WUE across large spatial extents and diverse ecosystems.

Several studies have examined different aspects of WUE research, from spatial and temporal patterns to the influence of climatic and biophysical factors. At the global and regional scales, satellite-based assessments have been used to examine long-term trends in WUE and its responses to climate change, land-use dynamics, and extreme weather events. For example, Huang and coauthors [14] examined global WUE patterns via MODIS-derived GPP and ET products, revealing distinct latitudinal gradients and sensitivities to drought conditions. Similarly, Peters and colleagues [4] highlighted global-scale changes in ecosystem WUE in response to rising atmospheric CO_2 and shifting climate regimes. At the local scale, more detailed analyses have been conducted in specific ecosystems or agroecosystems via a combination of remote sensing and ground-based data. In China, recent studies have applied MODIS data to evaluate WUE trends in cultivated areas [15–16], forest ecosystems [17–19], and grasslands [20]. Vietnam, however, remains significantly underrepresented in the WUE research landscape. Despite its diverse ecological zones and increasing land-use pressures, few studies have focused specifically on evaluating WUE patterns across different ecosystems within the country. This research gap highlights the urgent need for detailed and region-specific analyses to better understand WUE dynamics in Vietnam and support sustainable resource management.

The Central Highlands of Vietnam is a vital agro-ecological zone characterized by a unique mix of montane forests, agricultural plantations (e.g., coffee, pepper), and diverse ethnicities. This region plays a significant role in the Vietnamese agricultural economy while also serving as a biodiversity hotspot and watershed area for the surrounding lowlands. However, the region is increasingly exposed to climate pressures such as erratic rainfall, warming trends, and deforestation, all of which can significantly impact vegetation productivity and water resource dynamics [21-24]. Given its ecological and socioeconomic significance, the Central Highlands is an important yet understudied region for WUE research.

The primary aim of this study is to investigate the spatial and temporal dynamics of WUE and their responses to climate and soil moisture variables in the Central Highlands of Vietnam via satellite-derived time series data from 2001–2024. Specifically, this study aims to assess spatiotemporal patterns and long-term trends in WUE across different land cover types; (2) evaluate the influence of key climatic variables, such as precipitation, solar radiation, temperature, and soil moisture deficit, on WUE variability; and (3) identify spatial hotspots where WUE is particularly sensitive to climatic fluctuations, offering valuable insights for regional resource planning and adaptive management under changing environmental conditions.

Study and materials

1) Study area

The study area covers the Central Highlands of Vietnam (Figure 1), a key agroecological and socioeconomic region in the south-central part of the country. This region has five provinces (Dak Lak, Dak Nong, Kon Tum, Gia Lai, and Lam Dong) and spans approximately 55,000 km^2 with different land cover types (e.g., agriculture, forest, and built-up areas). Forests cover nearly 55% of the study area, whereas rainfed cropland accounts for approximately 23%. Geographically, the area features a complex topography of plateaus, hills, and highland basins with elevations ranging from 400 to over 2,000 m above sea level.

The Central Highlands experiences a tropical monsoon climate with two distinct seasons: a wet season from May to October and a dry season from November to April. The annual precipitation ranges from 1,200 to 1,800 mm, whereas the average temperature varies from 18°C to 25°C, depending on elevation [25]. These climatic conditions and fertile basaltic soils make the region an important hub for agricultural production, particularly for industrial crops such as coffee, pepper, cashew, and rubber. Notably, this region accounts for nearly 95% of Vietnamese coffee output [26].

2) Dataset

This study employed multiple datasets to examine WUE dynamics and their interactions with climate variables across the Central Highlands of Vietnam. Specifically, three primary datasets were used: MODIS GPP, MODIS ET, and ERA5-Land climate reanalysis data. These datasets were selected for their reliability, spatial and temporal resolution and relevance to ecosystem productivity and water fluxes. The GPP data were obtained from the MOD17A2H product, an 8-day composite dataset at a 500 m spatial resolution [27]. This product estimates the total carbon fixed by vegetation through photosynthesis and is derived via a light-use efficiency model [11, 28]. Similarly, the ET data were sourced from the MOD16A2 product, an 8-day composite with a 500 m resolution. The MODIS ET is computed on the basis of key biophysical parameters such as the leaf area index (LAI), net radiation, and surface meteorology to estimate actual evapotranspiration [29]. The GPP and

ET datasets used in this study were analysis-ready and covered the period from 2001–2024. These datasets underwent various preprocessing steps, including cloud masking and temporal gap filling. Specifically, we identified and removed cloud-contaminated pixels by utilizing the quality indicator layer associated with the datasets. Missing values due to cloud-related pixels were filled via linear interpolation from the nearest valid neighboring pixels [30–31], thereby preserving the temporal continuity and minimizing potential biases in the time series. These products were subsequently composited into monthly windows with a geographic coordinate system.

In addition to the MODIS GPP and ET products, this study also used ERA5-Land climate reanalysis data produced by the European Centre for Medium-Range Weather Forecasts (ECMWF). ERA5-Land provides high-resolution hourly estimates of climate variables such as precipitation, temperature, soil moisture, and solar radiation, making it particularly valuable for capturing temporal and spatial variability in climatic conditions [32]. Additionally, this study used MODIS land cover products from 2022 and reclassified them into seven classes (rainfed cropland, irrigated cropland, shrubland, mixed forest, evergreen forest, deciduous forest, and others) to examine the patterns of WUE across land cover types [33]. To ensure compatibility with the MODIS datasets, the ERA5-Land data were spatially resampled to a 500 m resolution via bilinear interpolation and subsequently exported in a geographic coordinate system for consistent spatial referencing. All these datasets, except the ESA CCI land cover product, were accessed via the Google Earth Engine (GEE) [34].

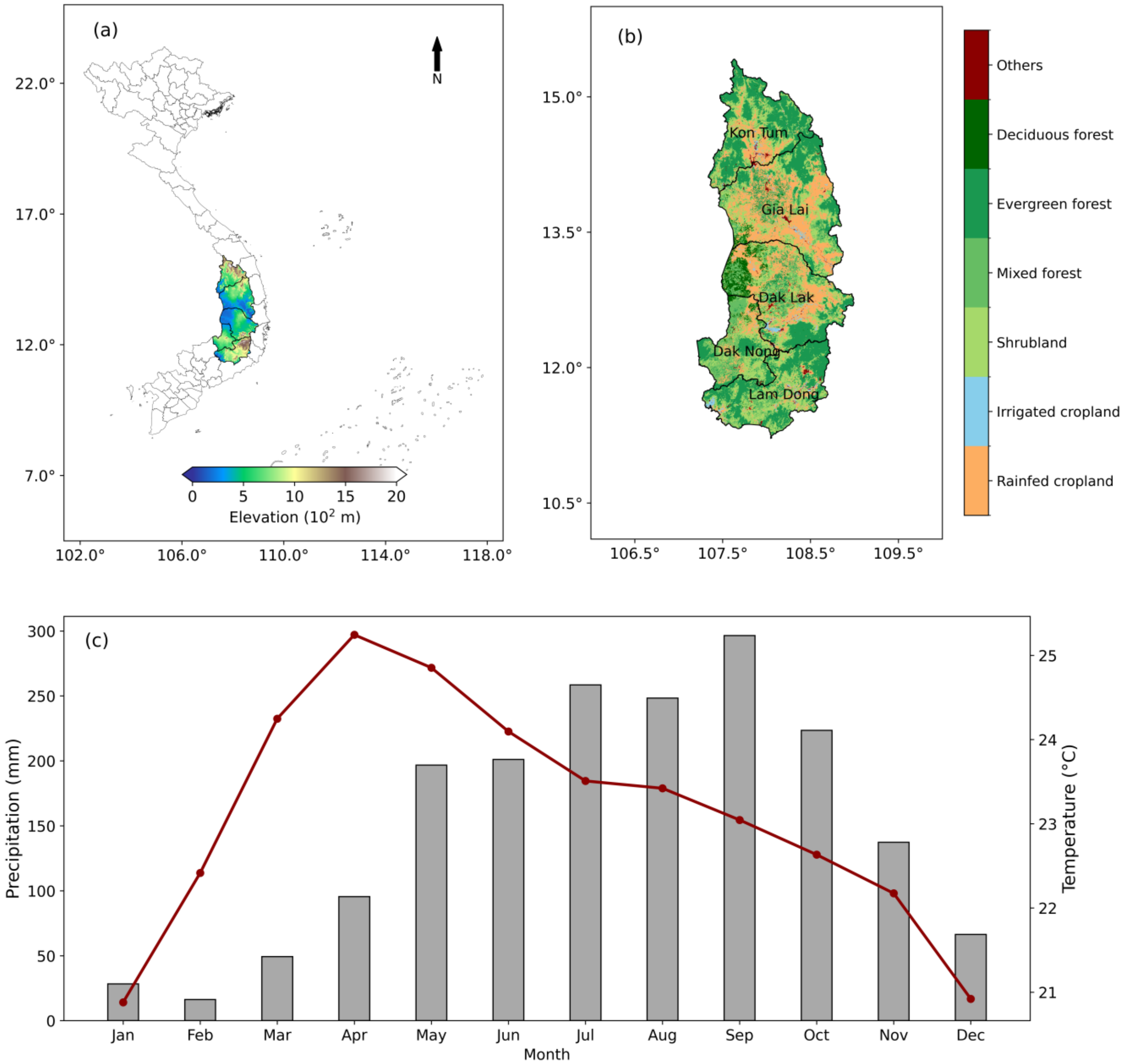

Figure 1 Geographic characteristics of the Central Highlands of Vietnam: (a) location and elevation of the study area within Vietnam, (b) distribution of major land cover types, and (c) monthly temperature and precipitation. The land cover data were derived from the ESA CCI land cover product (2022), whereas the precipitation and temperature data were extracted from ERA5-Land from 2001–2024.

Both the MODIS and ERA5-Land datasets used in this study have demonstrated robust accuracy and are commonly used for monitoring and assessing climate and water-related analyses at regional and global scales. Sabater and colleagues recently cross-validated ERA5-derived land variables across the globe and reported strong agreement with station-based measurements [35]. While no dedicated studies have yet assessed the performance of MODIS or ERA5-Land products, specifically in Vietnam, the continuous improvement and validation of these datasets globally suggest increasing reliability and applicability in regional contexts, including Vietnam.

3) Methods

3.1) Water use efficiency (WUE)

In this study, the WUE was calculated via the MODIS-based GPP and ET monthly from 2001–2024 over the Central Highlands of Vietnam. The WUE reflects the relationship between carbon assimilation and water consumption in terrestrial ecosystems and can be estimated via Eq. 1 [36–38]:

$$\mathrm{WUE} = \frac{\mathrm{GPP}}{\mathrm{ET}} \qquad \text{(Eq. 1)}$$

where GPP and ET indicate the monthly MODIS-based gross primary product (GPP) and evapotranspiration (ET), respectively, from 2001–2024. The WUE is a water use efficiency indicator that provides insight into how efficiently vegetation in the Central Highlands converts water into biomass over time.

To assess the deviations from a long-term WUE baseline, we further calculated the WUE anomaly. This index quantifies the standardized deviation of WUE from its multiyear average and is useful for identifying unusual or extreme changes in vegetation productivity relative to water use (Eq. 2).

$$\mathrm{WUE_{anomaly}} = \frac{\mathrm{WUE_i} - \mathrm{WUE_{mean}}}{\mathrm{WUE_{std}}} \qquad \text{(Eq. 2)}$$

Where $\mathrm{WUE_{anomaly}}$ represents the WUE anomaly index and where $\mathrm{WUE_i}$ represents the monthly WUE from 2001–2024. $\mathrm{WUE_{mean}}$ and $\mathrm{WUE_{std}}$ represent the mean and standard deviation values of the WUE, respectively, which are calculated monthly at each pixel (12 months) over the study period. A positive anomaly indicates higher-than-average WUE, suggesting more efficient water use relative to productivity, whereas a negative anomaly suggests reduced efficiency.

3.2) Trend analysis

This study used nonparametric methods to perform a statistical trend analysis of WUE from 2001–2024 to detect both the direction and magnitude of changes in WUE over time. Here, we used the nonparametric Mann–Kendall (MK) test to assess the statistical significance of monotonic trends in the WUE time series. This method has been commonly used to calculate trends in climate and environmental time series because of its robustness against autocorrelation and nonnormal data distributions [22, 39–40]. A positive MK test statistic indicates an increasing trend, whereas a negative statistic indicates a decreasing trend [38]. The significance of the trend was evaluated at the 95% confidence level ($p < 0.05$). Furthermore, this study quantifies the rate of change in WUE via Sen's slope estimator, a nonparametric method that calculates the median slope of all possible pairwise comparisons in the time series [40–41]. The resulting slope values represent a change in WUE over the study period. In this study, the MK test and Sen's slope estimation were applied pixelwise to generate spatial maps of trend significance and magnitude during the dry and rainy seasons.

3.3) Seasonal responses of WUE to climate and soil moisture

This study examined the spatial responses of WUE to climate and soil moisture variables during the dry and rainy seasons from 2001–2024. Here, we employed Spearman correlation analysis [30, 42, 43]. We first aggregated WUE separately for the dry and rainy seasons of each year, generating two distinct seasonal time series spanning the study period. This seasonal aggregation enabled us to capture the intra-annual variability in WUE and its potential sensitivity to changes in climatic conditions and soil moisture dynamics. For each season, we then calculated Spearman correlation coefficients between the WUE and four key variables: air temperature, precipitation, soil moisture, and solar radiation. This nonparametric method was chosen for its robustness in identifying monotonic relationships without assuming a linear distribution, making it particularly suitable for complex ecohydrological interactions [30, 44]. This analysis aimed to reveal how WUE responds differently to climatic drivers and soil moisture availability during dry and rainy periods, offering insights into the seasonal dependencies of ecosystem water use across the study region.

Results and discussion

1) Spatiotemporal variability in water use efficiency

Figure 2 shows the spatial and temporal patterns of the WUE anomalies across the Central Highlands of Vietnam from 2001–2024. Overall, there were distinct interannual and spatial variabilities in WUE. For example, multiple years (e.g., 2004, 2015, and 2021–2024) present widespread positive anomalies (Figure 2), suggesting periods of enhanced vegetation performance and potentially favorable hydroclimatic conditions. In contrast, the periods of 2005–2008, 2010–2013, and 2016–2017 were characterized by dominant negative anomalies (Figure 2), indicating reduced water use efficiency across vegetation ecosystems. These declines likely reflect the impacts of significant environmental stressors, including prolonged droughts, elevated temperatures, and ongoing land degradation. Notably, these years coincided with well-documented severe drought events in the region, during which vegetation ecosystems presented signs of physiological stress, reduced productivity, and diminished resilience [23, 24, 30, 45].

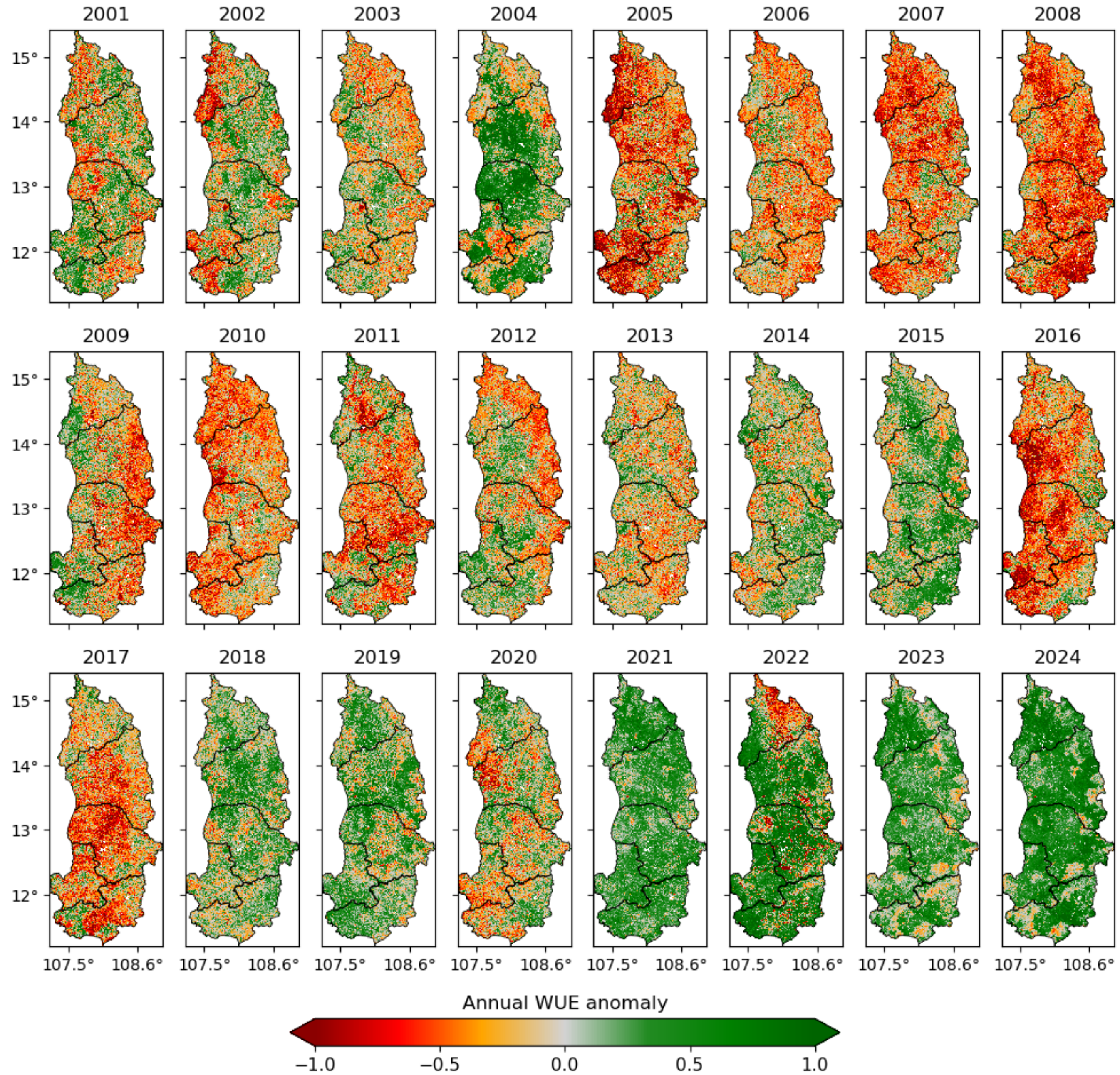

Figure 2 Annual patterns of WUE anomalies in the Central Highlands of Vietnam from 2001–2024. Dark red indicates a lower WUE, whereas dark green represents higher WUE values.

Spatially, the anomalies are heterogeneously distributed across the region. The northern and eastern subregions display more pronounced variability (Figure 2), which is likely influenced by altitudinal gradients, land cover differrences (e.g., forest vs. cropland), and microclimatic variability. Notably, the recent trend from 2021 onward shows a shift toward consistently positive WUE anomalies (Figure 2), suggesting possible ecological recovery, improved agricultural practices, or climate-driven shifts favoring vegetation productivity. More than 80% of the study area recorded positive WUE values in recent years (Figure 2). In 2021, for example, approximately 90% of the region demonstrated positive WUE anomalies. In contrast, during 2008, nearly 89% of the area experienced negative WUE, indicating widespread water stress and reduced ecosystem efficiency.

Figure 3 shows the spatial distribution of the monthly WUE values across the Central Highlands of Vietnam, which were averaged over the 24-year period from 2001–2024. The map reveals a somewhat seasonal cycle in WUE. During the early dry season (January–April), the region is dominated by low WUE values, particularly in the northern and eastern areas (Figure 3). These months are characterized by high solar radiation and limited rainfall [25], resulting in increased evapotranspiration and water stress, which may constrain plant productivity. April presented one of the lowest regional WUE patterns, likely reflecting the cumulative effects of dry season stress. Similarly, lower WUE values were observed in May and June. From July to August, the WUE gradually increased, with spatial patterns showing a mix of moderate to high values. This period corresponds with the onset and peak of the monsoon season [46], which improves soil moisture conditions and facilitates more efficient vegetation growth. Notably, August and September present widespread areas of relatively high WUE, particularly in the southern and central zones, indicating a favorable balance between water availability and carbon assimilation. The postmonsoon and transition months (October–December) presented the highest WUE values across the region, especially in October and November. This peak may result from residual soil moisture combined with a reduction in atmospheric demand, allowing plants to maintain high photosynthetic activity with less water loss. December shows a slight decline, as the region transitions back into the dry season.

The spatial and temporal patterns derived in this study offer critical insights into how the WUE functions and is distributed across the Central Highlands of Vietnam. These patterns reveal important trends and disparities that can inform both scientific understanding and practical decision-making. For example, consistently lower levels of WUE were observed in the northern and southern parts of the study area. These findings suggest that these regions may be more vulnerable to water stress or less efficient in converting water into biomass, possibly because of factors such as land degradation, soil quality, or suboptimal land management practices. As a result, these areas warrant greater attention in the development of targeted water resource management policies, optimized land use planning, and the implementation of climate-resilient agricultural strategies.

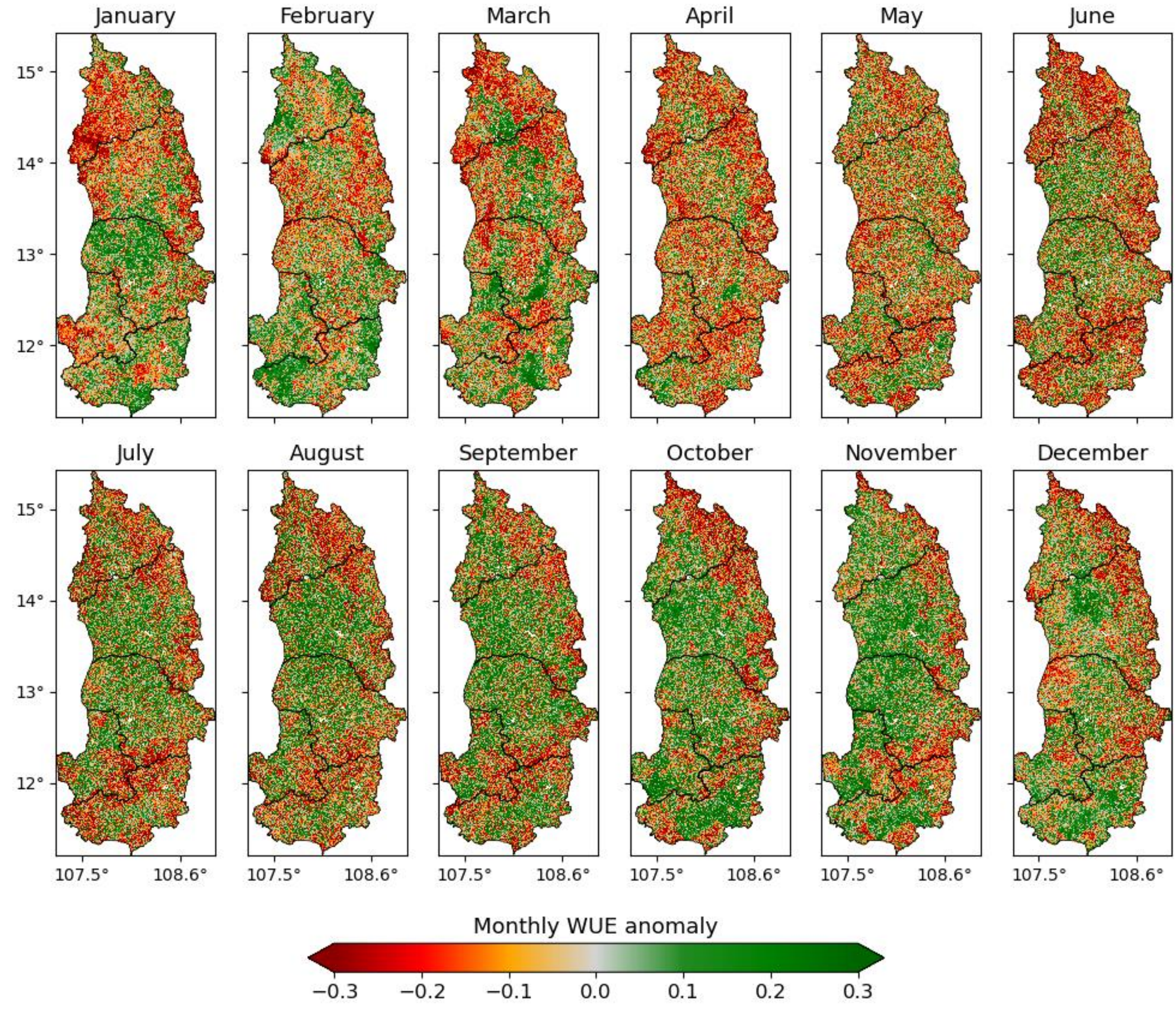

Figure 3 Monthly patterns of WUE anomalies in the Central Highlands of Vietnam from January to December during the study period. Dark red indicates a lower WUE, whereas dark green represents higher WUE values.

With respect to the WUE variability across land cover types, Figure 4 shows the monthly time series of WUE anomalies across rainfed croplands and forests from 2001–2024. The color represents the WUE direction and intensity, with green denoting positive deviations and dark red denoting negative deviations from the mean. Rainfed croplands show high interannual variability with distinct periods of severe negative anomalies, particularly between 2005 and 2010, suggesting episodes of water stress or reduced productivity. Similarly, the irrigated areas also experienced negative anomalies. During this period, the study region experienced multiple drought events, and the months with the lowest WUE values were aligned with the reported drought months in recent studies [22, 47]. However, from approximately 2020 onward, there is a noticeable and consistent trend of positive anomalies, which is aligned with the spatial pattern in Figure 2. In contrast, forests exhibit relatively smaller fluctuations with a steadier baseline, although a similar trend of increasingly positive anomalies has been evident in recent years. This contrast highlights land cover-specific responses to climatic and environmental changes in the region.

Notably, rainfed and irrigated croplands presented similar WUE variabilities over the study period, which is likely due to the small portion of irrigated croplands. According to the ESA CCI land cover product, irrigated cropland accounts for only approximately 1.1% of the total land area in the study area. Moreover, irrigated fields in this region are typically small and highly fragmented, making them difficult to distinguish via global land cover products with moderate spatial resolution. As a result, land cover classification may underestimate the true extent of irrigated areas, potentially limiting the ability to detect distinct WUE patterns between irrigated and rainfed systems.

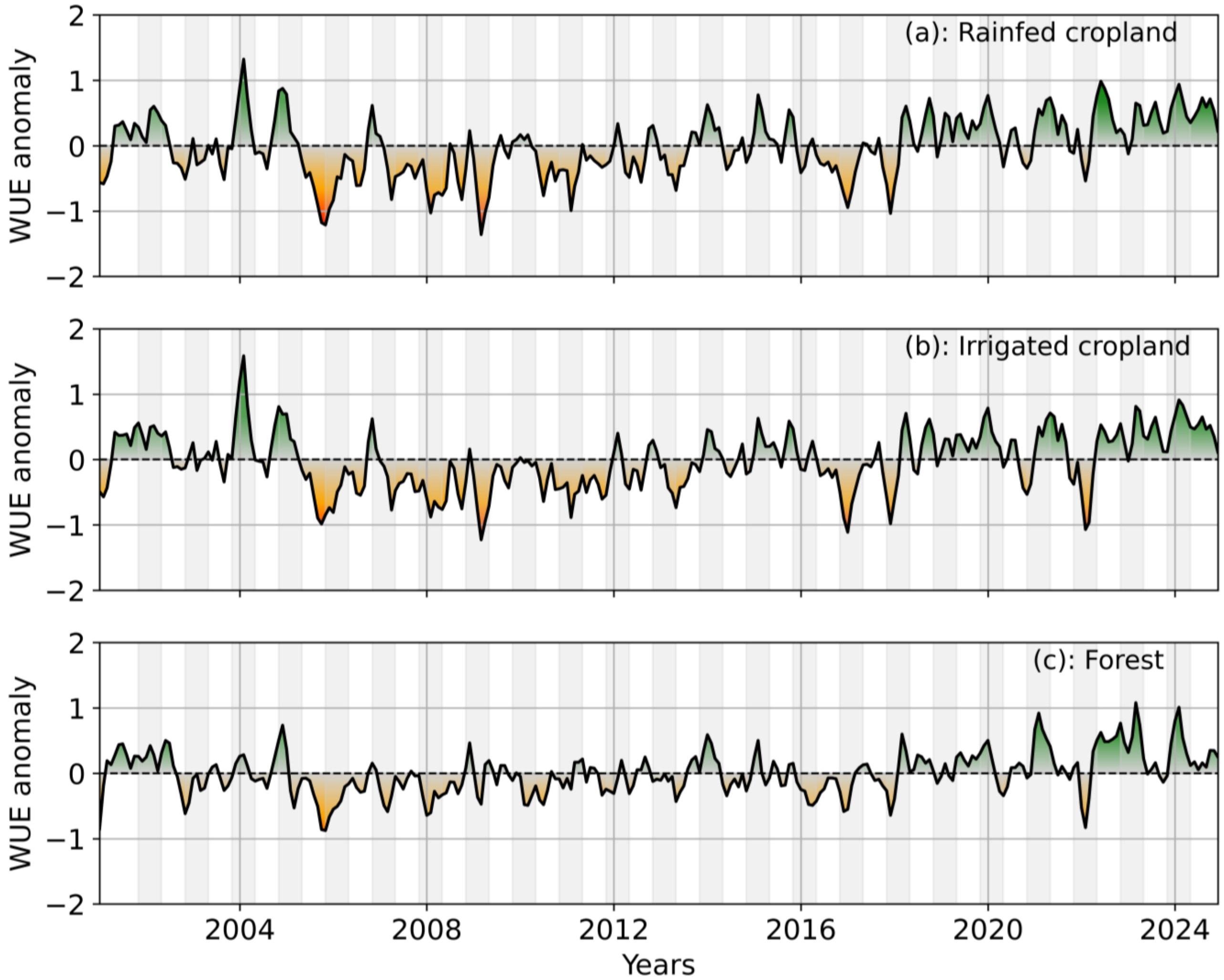

Figure 4 Time series evolution of the monthly WUE across rainfed croplands (a) and forests (b) across the study area from 2001–2024. Dark gray indicates the dry season.

2) Spatial WUE trend

The spatial trend in WUE is exhibited across the Central Highlands of Vietnam for the dry and rainy seasons over the period 2001–2024 (Figure 5). Each pixel represents a statistically significant trend in WUE, color-coded by magnitude and direction. Positive trends (in green) suggest increasing WUE, whereas negative trends (in red) indicate declining WUE. The intensity of the color corresponds to the strength of the trend, as shown by the diverging color map at the bottom. Despite spatial variability, both seasons experienced large positive trends from 2001–2024.

During the dry season, strong spatial heterogeneity in the WUE trends was observed. Large contiguous areas, particularly in the northern and southern parts of the region (Figure 5), show positive WUE trends, indicating improved water-use efficiency in these dry-season months. These positive trends may reflect shifts in land management practices, crop selection favoring drought-tolerant varieties, or adaptive responses to prolonged dry conditions. However, notable clusters of negative trends are found, especially in the central–western zone, which could point to areas facing persistent water stress, land degradation, or unsustainable land use. Additionally, the central areas experienced stable WUE trends, such as those in Dak Lak Province (Figure 5), and these areas were largely associated with coffee plantations and industrial crops [48].

During the rainy season, the positive trends in WUE are even more widespread (Figure 5), covering much of the northern and central portions of the region. Nearly 35% of the studies reported positive trends, whereas nearly 62% reported nonsignificant trends. This pattern suggests that ecosystems, especially vegetation, may respond favorably to localized seasonal rainfall, possibly due to improved soil moisture availability, increased photosynthetic activity, or increased vegetation cover. While negative trends are present, they are more spatially scattered and less extensive than they are in the dry season. These pockets of decline could be associated with localized land-use changes, deforestation, or urban expansion interfering with natural water and carbon fluxes. The overall increasing trends during both dry and rainy seasons were aligned with global and regional studies [14, 17].

The spatial patterns of the WUE trends observed in this study are likely linked to land management practices in the Central Highlands. For example, regions showing increasing WUE trends may indicate that good land use practices, such as agroforestry integration and contour farming, have been promoted by local authorities and agricultural extension services. Conversely, areas with declining or stagnant WUE trends tend to overlap with zones affected by land degradation or unregulated deforestation, which can reduce soil moisture retention and overall productivity. A recent study surveyed coffee farmers in the Central Highlands, specifically in Lam Dong Province, and revealed that farmers with improved irrigation methods have significantly increased water use efficiency [49]. While this study relies primarily on satellite-derived data, qualitative insights from local stakeholders and previous field-based studies suggest that fragmented land ownership, inconsistent enforcement of land-use policies, and limited access to technical support have contributed to the uneven adoption of sustainable practices [35, 50]. The incorporation of such socioenvironmental dynamics provides a more nuanced understanding of how land management influences water use efficiency across a region, underscoring the need for integrated land and water governance strategies.

3) Spatial response of WUE to climate and soil moisture

The spatial patterns of the correlation coefficients between the WUE anomalies and key climate variables in the Central Highlands of Vietnam from 2001–2024 reveal distinct seasonal differences. Compared with the rainy season, during the dry season (Figure 6), the WUE exhibited stronger and more widespread responses to climate drivers (Figure 7). For example, WUE showed notable positive correlations with solar radiation (Figure 6b), especially in the southern and central parts of the region, indicating that higher temperatures and increased radiation during the dry season could increase WUE. In contrast, WUE was negatively correlated with soil moisture (Figure 6d) and rainfall (Figure 6c) across extensive portions of the landscape, covering nearly 50% of the study area. This suggests that water availability constraints intensify the WUE during drier periods, as vegetation may optimize carbon assimilation under water-limited conditions. Moreover, the correlations between temperature and WUE were largely nonsignificant, with approximately 80% of the area showing no detectable response.

In contrast, during the rainy season, the relationships between WUE and climate and soil variables were considerably weaker and exhibited greater spatial uniformity (Figure 7). Statistically, only approximately 12% of the study region presented a significant positive response of WUE to temperature (Figure 7a), whereas responses to other climate variables were significant in less than 5% of the area. The correlations were generally sparse and weakly distributed across the region, suggesting that during periods of abundant rainfall, WUE becomes largely insensitive to variations in temperature, radiation, soil moisture, and precipitation. The stable responses during the rainy season highlight the buffering effect of plentiful water availability, leading to reduced climatic stress on plant physiological processes. Overall, these results emphasize that the WUE in the Central Highlands is more vulnerable to climatic variability during the dry season. Conversely, during the rainy season, the WUE remains relatively stable and is less influenced by environmental fluctuations.

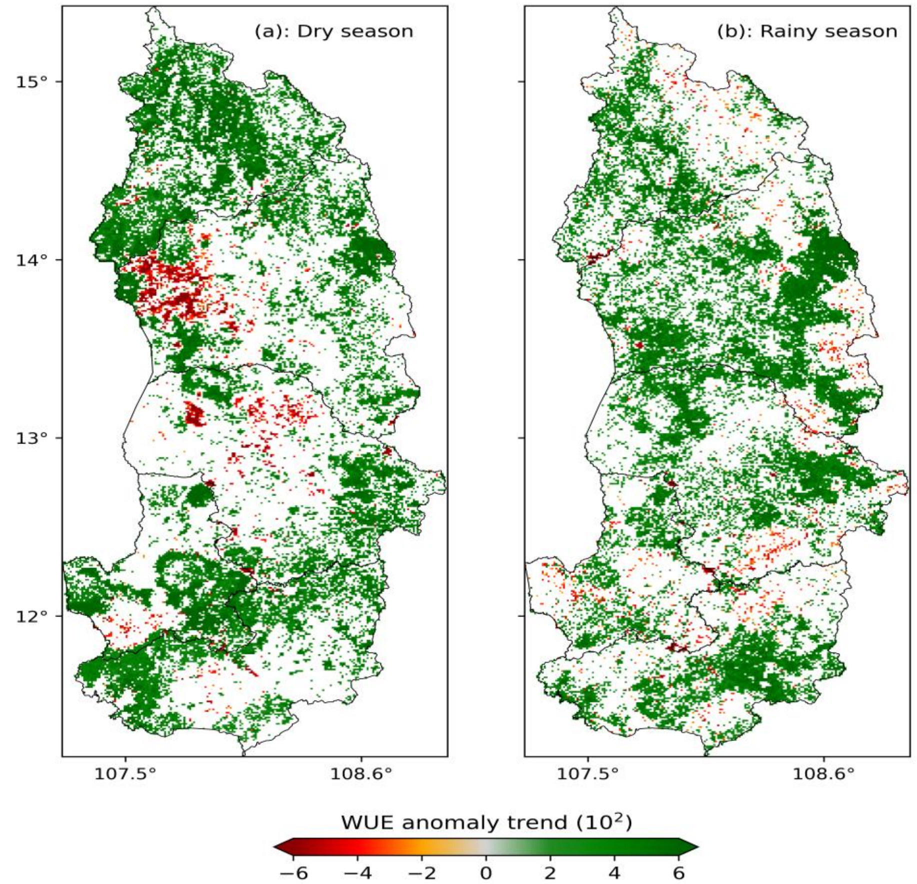

Figure 5 Spatial trend of the WUE anomalies across the Central Highlands of Vietnam during the dry and rainy seasons from 2001–2024. Areas shaded in dark red indicate a statistically significant decline in WUE, whereas dark green areas reflect a significant increase in WUE at the 95% confidence level. The white areas represent pixels where changes in WUE are not statistically significant, suggesting stable or uncertain trends over the study period.

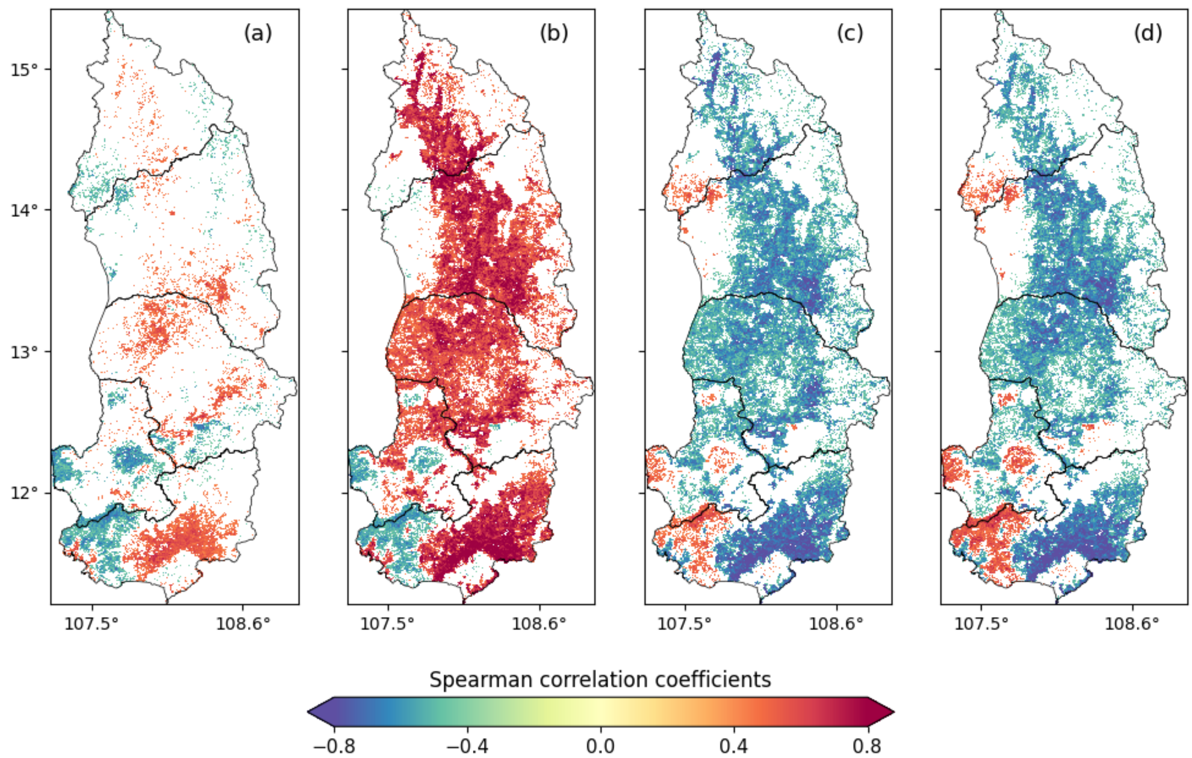

Figure 6 Spatial patterns of WUE anomalies in response to climate variables (a: temperature, b: solar radiation, c: precipitation) and soil moisture (d) during the dry season from 2001–2024. The dark red regions indicate strong positive correlations, whereas the dark blue regions represent strong negative correlations. The white areas denote locations where the responses are not statistically significant.

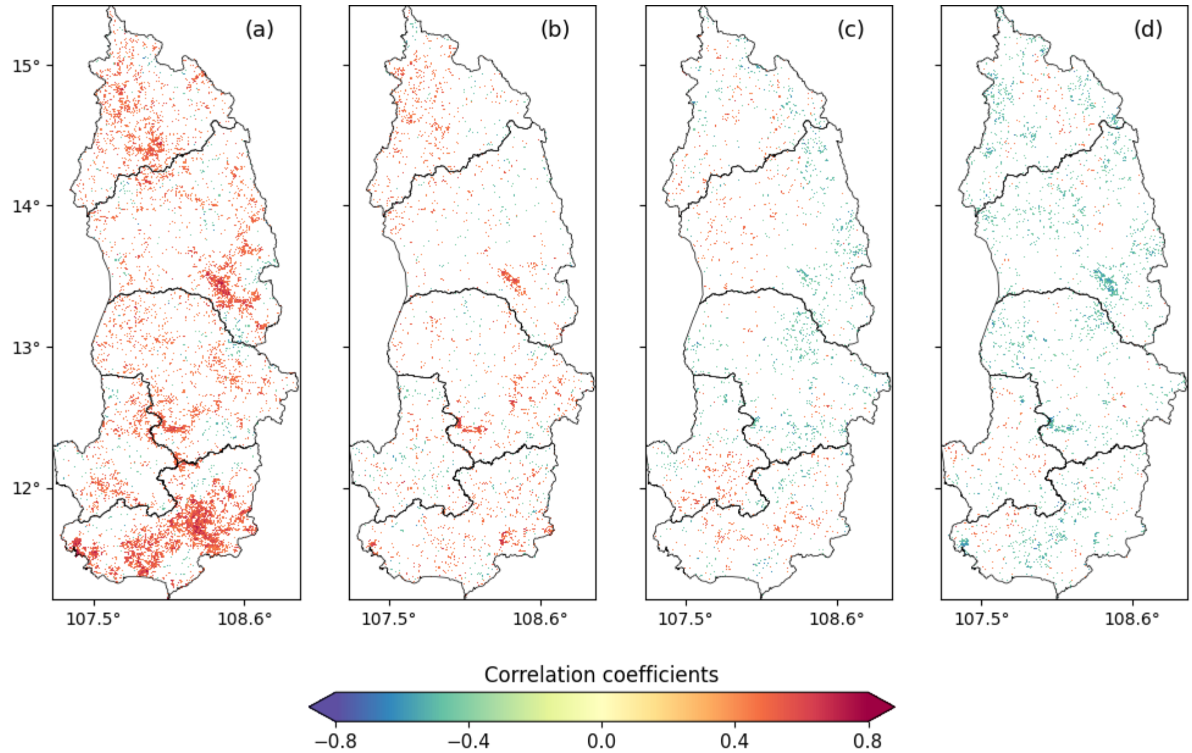

Figure 7 Spatial patterns of WUE anomalies in response to climate variables (a: temperature, b: solar radiation, c: precipitation) and soil moisture (d) during the rainy season from 2001–2024. The dark red regions indicate strong positive correlations, whereas the dark blue regions represent strong negative correlations. The white areas denote locations where the responses are not statistically significant.

This pattern is consistent with our previous study on the impacts of drought events on vegetation ecosystems [23], which also revealed that vegetation productivity was significantly more affected during the dry season, whereas impacts were notably weaker during the rainy season. The heightened vulnerability in the dry season is likely due to limited water availability, which constrains photosynthetic activity and plant growth. In support of this, a recent study further investigated the response of WUE to drought conditions and reported a strong sensitivity of WUE to drought stress [14]. This suggests that WUE can serve as a reliable indicator of ecosystem response to water limitations, as it integrates both carbon assimilation and water loss processes. The observed decline in WUE under drought conditions reflects reduced photosynthetic rates coupled with ongoing or increased evapotranspiration, indicating a decline in ecosystem function and resilience.

These findings have important implications for understanding ecosystem resilience and agricultural sustainability in the study region. The responses of WUE to climatic variables during the dry season suggest that vegetation productivity and water use strategies are highly vulnerable to intensifying drought conditions, a concern that has been increasingly highlighted in recent regional and local studies [23–24, 30]. The negative correlations with soil moisture and rainfall align with previous research showing that water scarcity is a major limiting factor for crop yields and forest health in this region [51–52]. Furthermore, the positive association with solar radiation indicates that light availability plays a critical role in regulating WUE during dry periods, supporting earlier observations that photosynthetic activity in the Central Highlands peaks under clear-sky conditions when water is moderately available. These dynamics underscore the need for adaptive land management strategies, such as optimizing irrigation practices and enhancing soil moisture retention, to sustain ecosystem functioning under projected climate variability and drought frequency increases.

4) Limitations and future research

This study presents a detailed analysis of the WUE and climate influence across the Central Highlands of Vietnam from 2001-2024; however, it still has several limitations. While the WUE-based MODIS product offers long-term and consistent observations at moderate spatial resolution (e.g., 500 m), it may not capture fine-scale variability in vegetation structures, land management practices, and microclimate conditions. Additionally, the MODIS-based time series used in this study have been carefully preprocessed, but inherent limitations associated with remote sensing data remain, such as atmospheric interference and sensor calibration drift [53–54]. These issues may introduce uncertainty in heterogeneous landscapes such as the Central Highlands, where agricultural plots are often small and fragmented.

Another limitation can be associated with land cover classification products. This study considered two main vegetation types in the vegetation-WUE response analysis. While this approach helps identify general differences in WUE between forest and cropland types, it does not capture the details of specific crop responses to WUE in the region. The Central Highlands of Vietnam are home to a diverse range of crop types, including coffee, pepper, and cashew, each of which exhibits distinct water use and carbon assimilation patterns. However, given the lack of detailed crop types in the region, such an analysis may be the focus of future studies.

Finally, this study utilized monthly time series and presented seasonal and annual analyses of WUE over the past two decades. Hence, short-term fluctuations in WUE, driven by weather extremes, irrigation events, or crop growth cycles, are likely underrepresented in our aggregated analysis. This study also does not account for the potential influence of future climate change on WUE patterns. The incorporation of climate model projections and scenario-based analyses in future work would offer a more comprehensive understanding of how WUE may evolve under different climate pathways. For example, increased temperatures could intensify evaporative demand and alter plant physiological responses, potentially reducing WUE in water-limited ecosystems. Such an approach could help identify future hotspots of vulnerability or resilience and support the development of targeted adaptation strategies for sustainable agriculture and forest management in the face of ongoing climate change.

Conclusions

This study provides a detailed assessment of the spatial and temporal variability in water use efficiency (WUE) in the Central Highlands of Vietnam from 2001–2024. This reveals strong interannual fluctuations and distinct seasonal patterns of WUE and their response to climatic and environmental factors over the study period. Higher WUE values were detected in 2004, 2015, and 2021–2024, whereas lower WUE values were detected in 2005–2008, 2010–2013, and 2017–2018. For example, nearly 89% of the study area experienced water use stress in 2008. In contrast, 2021 presented the greatest extent of improved WUE conditions, with approximately 90% of the study area exhibiting positive WUE responses. Land cover-specific water use results in a higher WUE in rainfed cropland than in forest ecosystems. The spatial response of WUE to climate and soil variables revealed that the dry season presented stronger and more heterogeneous responses to climate variables, particularly soil moisture and solar radiation, whereas the rainy season presented more stable WUE dynamics, buffered by abundant water availability. Additionally, the trend analysis revealed that the positive trends in WUE observed in recent years suggest potential ecological recovery and improved land management practices, although pockets of vulnerability remain. These findings emphasize the critical role of adaptive strategies in sustaining vegetation productivity and ecosystem resilience under increasing climate variability. Future efforts should focus on integrated water resource management, climate-smart agriculture, and ecosystem conservation to increase the sustainability and resilience of the Central Highlands landscape in the face of ongoing environmental change.

Acknowledgements

We acknowledge NASA, the Google Earth Engine team, and the ERA5 data providers (ECMWF) for making high-quality, open-access datasets available, which were essential for conducting this study.

Data availability

This study utilized publicly available datasets accessed through the Google Earth Engine computing platform, including MODIS GPP (https://doi.org/10.5067/MODIS/MOD17A2H.061), MODIS ET (https://www.umt.edu/numerical-terradynamic-simulation-group/project/modis/),and ERA5-Land (https://cds.climate.copernicus.eu/datasets).

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