Impacts of changes in evapotranspiration on the availability and effectiveness of water resources in the Qilian Mountains (postprint)

Authors: Xin Huijuan, Xu, Li Zongsheng, Yang Liqin, Wang Yunying

Date: 2026-01-30T16:53:16+00:00

Abstract

Against the backdrop of global warming and vegetation greening, elucidating the impact of evapotranspiration (ET) on water resources in arid regions is of critical importance. Taking the Qilian Mountains (QLM) as a case study, this research, based on GLEAM data and employing trend analysis and structural equation modeling, quantitatively analyzes the spatiotemporal characteristics and driving mechanisms of ET and its components (plant transpiration T and soil evaporation E) during 2000–2023, as well as their effects on water resource availability (WA, WA/Pre) and effectiveness (T/ET, T/Pre). The results show that ET increased significantly (1.58 mm·a-1), mainly driven by the increase in T (1.79 mm·a-1), with T/ET (0.004 a-1) continuously rising, indicating enhanced water resource effectiveness. Precipitation (Pre) is the dominant environmental factor controlling ET variations, while T is driven by leaf area index (LAI, total effect 0.90), and T/ET responds primarily to changes in temperature (Tem, total effect 1.68); Tem is also the dominant factor influencing E (total effect -0.748). Although the increase in LAI enhances water resource effectiveness by increasing T, the decrease in Pre combined with the increase in ET leads to a reduction in WA and thus a decline in water availability. This indicates that although the increase in ET (especially T) improves water use efficiency, it intensifies water scarcity. Therefore, balancing the T/E ratio is key to alleviating this contradiction. This study can provide a reference for ecological restoration and sustainable water resources management in arid regions under climate change.

ChinaRxiv 中X

Full Text

Impacts of Evapotranspiration Variability on the Availability and Effectiveness of Water Resources in the Qilian Mountains

XIN Huijuan[1], XU Chong[1], LI Zongxing[2],[3], YANG Liqin[3], WANG Yunying[2]

[1]Key Laboratory of Yellow River Water Environment, Lanzhou Jiaotong University, Lanzhou 730070, Gansu, China
[2]Observation and Research Station of Eco-Hydrology and National Park by Stable Isotope Tracing in Alpine Region, Gansu Qilian Mountains Ecology Research Center, State Key Laboratory of Ecological Safety and Sustainable Development in Arid Lands, Northwest Institute of Eco-Environment and Resources, Chinese Academy of Sciences, Lanzhou 730000, Gansu, China
[3]College of Geography and Environmental Science, Northwest Normal University, Lanzhou 730070, Gansu, China

Abstract

Under the dual contexts of global warming and vegetation greening, clarifying the impacts of evapotranspiration (ET) on water resources in arid regions is of critical importance. Focusing on the Qilian Mountains as a case study, this research quantitatively examined the spatiotemporal characteristics and driving mechanisms of ET and its components—plant transpiration (T) and soil evaporation (E)—and their effects on water resource availability (WA, WA/Pre) and effectiveness (T/ET, T/Pre) from 2000 to 2023. Using GLEAM data products, trend analysis, and structural equation modeling, we found that ET increased significantly at a rate of 1.58 $\mathrm{mm \cdot a^{-1}}$, primarily driven by the growth of T (1.79 $\mathrm{mm \cdot a^{-1}}$). The T/ET ratio increased continuously at 0.004 $\mathrm{a^{-1}}$, indicating enhanced water resource effectiveness. Precipitation (Pre) emerged as the dominant environmental factor controlling ET variation, while T was mainly driven by leaf area index (LAI) with a total effect of 0.90. Air temperature (Tem) was the primary factor influencing both the T/ET ratio (total effect 1.68) and E (total effect −0.748). Although ET growth—particularly in T—enhanced water use efficiency, it also intensified water scarcity by reducing water availability. This suggests that while vegetation restoration improves water resource effectiveness, the combined pressures of decreasing precipitation and increasing ET, especially the E component, must be carefully managed. Balancing the trade-off between T and E thus represents a key strategy for reconciling these competing dynamics. These findings provide a scientific basis for ecological restoration and sustainable water resource management in arid regions under climate change.

Keywords: evapotranspiration; water availability and effectiveness; vegetation restoration; Qilian Mountains

Introduction

Arid regions exhibit significant changes in hydrological processes against the backdrop of global climate change and vegetation restoration. These regions are critical for achieving land degradation neutrality targets, and the success of vegetation restoration as a primary measure depends heavily on water resource availability and effectiveness. Evapotranspiration (ET) serves as a key component of the water cycle, and its continuous variation under climate change directly impacts terrestrial water availability. Global land ET has shown a significant increasing trend, with profound implications for global water cycling, ecosystem functioning, and water resource availability that have attracted widespread attention. Accurately characterizing ET dynamics and quantifying the influence of environmental factors is therefore essential for water resource and ecosystem management in arid regions.

Global ET has changed dramatically over recent decades, with spatiotemporal evolution and driving mechanisms showing regional differences. While temperature rise is the main cause of ET increase at the global scale, precipitation and wind speed dominate in China, with precipitation change explaining 57% of ET variation across mainland China. In addition to hydrothermal conditions, vegetation cover affects ET through transpiration, and global vegetation greening is considered an important reason for ET enhancement. Although previous studies have revealed complex regulatory mechanisms of climate and vegetation on ET, research on ET components remains insufficient, limiting deeper understanding of water resource redistribution mechanisms. Because different ET components respond differently to climate and vegetation, and their varying change patterns ultimately affect the effectiveness and availability of terrestrial water resources, component-based ET research can improve understanding of ecosystem water use pathways and reveal how arid region water cycles respond to atmospheric and vegetation dynamics.

The Qilian Mountains, a critical ecological barrier in northwestern China, are highly sensitive to climate change and vegetation variation. In recent years, significant changes in soil and water conservation functions have profoundly affected regional water resource recharge and sustainability. Since implementing ecological engineering, vegetation coverage has increased rapidly from 48.86% to 65.84%, but vegetation restoration may also intensify water consumption through enhanced transpiration, potentially reducing regional water availability. Current research mostly focuses on total ET changes, while quantitative analysis of ET components and their responses to environmental factors remains lacking, making it difficult to reveal water resource redistribution mechanisms under climate-vegetation interactions. This study focuses on the Qilian Mountains region to explore the responses of ET and its components to vegetation and climate changes, and further analyze their impacts on water resource availability and effectiveness, providing theoretical support for optimized water resource management and ecological restoration in arid regions.

Study Area

The Qilian Mountains region (36°30′-39°30′N, 93°30′-103°E) is located in the northeastern Tibetan Plateau [Figure 1: see original paper]. Influenced by the interaction of the Siberian High, East Asian monsoon, and westerly jet stream, the region is highly sensitive to climate change. The area features both continental and alpine climate characteristics, with an average annual temperature of −2.6 °C that decreases with elevation. Precipitation is relatively abundant, with a multi-year average of 514 mm that gradually decreases from east to west. Various ecosystems exist, with grassland being the most widely distributed ecosystem type. In recent years, combined effects of global warming and extreme weather have significantly altered the region' s water and soil conservation functions, profoundly affecting water resource sustainability. Alpine grassland degradation and biodiversity decline have occurred, with meadow ecosystems being particularly vulnerable due to cold, dry conditions and external changes that affect ecosystem stability and regional hydrological characteristics.

Data and Methods

ET and Its Components This study used ET and soil moisture data from the Global Land Evaporation Amsterdam Model (GLEAM v4.2a), a global dataset with 0.25° spatial resolution available at monthly and annual scales from https://www.gleam.eu/. Based on satellite and reanalysis data, GLEAM has been validated and applied at multiple sites and basin scales in China. ET is partitioned into transpiration (T) and evaporation (E), where E includes snow sublimation (ES), open water evaporation (EW), interception loss (EI), and bare soil evaporation (EB). We calculated monthly E values by summing ES, EW, EI, and EB. This study primarily analyzed changes in ET and its components and their impacts on regional water resource availability and effectiveness.

Environmental Variables Environmental variables included climate, vegetation, and land cover. Climate data comprised precipitation (Pre) and air temperature (Tem) from the ERA5 reanalysis dataset, which contains monthly data from 1979 to present at 0.1°$×$0.1° resolution with a lag of about 3 months. Vapor pressure deficit (VPD) was calculated from dewpoint temperature. Soil moisture (SM) data were obtained by summing root zone and surface soil moisture from ERA5-Land. Leaf area index (LAI) data from MODIS (MOD15A2H-061) provide 500 m composite data at 8-day intervals from 2000–2023. Using the maximum value method, we obtained monthly LAI series to minimize cloud, aerosol, snow, and shadow effects. Land cover data used the 30 m annual China Land Cover Dataset (1985–2023) from Wuhan University professors Yang Jie and Huang Xin, with overall accuracy of 79.31%. We reclassified land use into cropland, forest, grassland, and water/wetland ecosystems, with other land types grouped as "other ecosystems." All raster calculations were performed using ArcGIS and Python.

Trend Analysis We used the Theil-Sen slope estimator combined with Mann-Kendall test to analyze ET trends and significance. This method, recommended by the World Meteorological Organization, is robust for meteorological, hydrological, and vegetation change analysis. The Theil-Sen slope quantifies ET change trends, where β represents the trend magnitude (positive β indicates increasing ET, negative β indicates decreasing ET). The Mann-Kendall test assesses trend significance. With sample size $n > 10$, we used Z-statistics with significance level $\alpha = 0.05$ ($Z_{0.05} = 1.96$). Following Wang et al., we defined four trend levels: significant increase ($\beta > 0$, $p < 0.05$), slight increase ($\beta > 0$, $p > 0.05$), significant decrease ($\beta < 0$, $p < 0.05$), and slight decrease ($\beta < 0$, $p > 0.05$).

Structural Equation Model Structural equation modeling (SEM) is an advanced multivariate statistical method that effectively handles complex interactions among multiple variables, reflecting direct, indirect, and total effects while allowing error terms, thus overcoming limitations of traditional statistical methods. This study used Bayesian SEM to analyze environmental influences on ET components. Bayesian SEM introduces prior distributions for parameters, combines prior information with observational data, and derives posterior distributions based on Bayes' theorem:

$$p(\theta|D) \propto p(\theta) \times p(D|\theta)$$

where θ represents model parameters (e.g., path coefficients), D is observational data, $p(\theta)$ is the prior distribution, $p(D|\theta)$ is the likelihood function, and $p(\theta|D)$ is the posterior distribution.

Using monthly raster data from 2000–2023, we extracted mean values from each grid cell as input variables for SEM. We established Bayesian SEM models containing environmental variables (Pre, Tem, VPD, SM, LAI) and ET components (T, E, T/ET). Path coefficients used normal priors (coefficient $\sim$ normal$(0, 1)$; intercept $\sim$ normal$(0, 10)$). We used Markov Chain Monte Carlo (MCMC) with two chains of 2,000 iterations each (including warm-up). Model convergence was assessed when all parameters had $\hat{R} < 1.05$ and effective sample sizes were sufficient. Path relationships were considered significant when 95% confidence intervals excluded zero. Total effects were calculated as the sum of direct and indirect effects. We used the Leave-One-Out Information Criterion (LOOIC) for model comparison, where lower values indicate better fit.

Results

Spatiotemporal Patterns of Environmental Variables At the interannual scale, precipitation increased at 0.48 $\mathrm{mm \cdot a^{-1}}$ from 2000–2013, but decreased at -2.19 $\mathrm{mm \cdot a^{-1}}$ thereafter ($p < 0.05$), with a multi-year average of 513.98 mm. The 2015 anomaly (264.35 mm) was significantly lower than other years since 2000, caused by high temperatures and drought from Arctic air masses and East Asian monsoons. Spatially, precipitation decreased from south to north due to topography and atmospheric circulation [Figure 2: see original paper]. About 51.39% of the region showed decreasing precipitation trends, particularly in the east, with 48.61% showing slight increase trends concentrated in central areas and near Qinghai Lake, but no significantly increasing regions.

Leaf area index increased significantly at 0.010 $\mathrm{a^{-1}}$ ($p < 0.05$) from 2000–2023, with a multi-year average of 0.85. Spatially, LAI decreased from southeast to northwest [Figure 3: see original paper]. Approximately 89.85% of the region showed increasing trends, with 39.24% significantly increasing, mainly in central and eastern areas. These results demonstrate overall vegetation greening, though some local areas showed decreasing trends due to climate change and human activities.

Spatiotemporal Changes in Evapotranspiration ET showed a significant increasing trend at 1.58 $\mathrm{mm \cdot a^{-1}}$ ($p < 0.05$), with a multi-year average of 252.85 mm [Figure 4: see original paper]. ET components showed contrasting patterns: E decreased insignificantly at -0.21 $\mathrm{mm \cdot a^{-1}}$ ($p > 0.05$), while T increased significantly at 1.79 $\mathrm{mm \cdot a^{-1}}$ ($p < 0.05$). The higher T growth rate relative to E's decline rate made T the primary driver of ET increase. The T/ET ratio increased significantly at 0.004 $\mathrm{a^{-1}}$ ($p < 0.05$), indicating vegetation greening drives ET component shifts, channeling more water through transpiration and making T the dominant ET component.

Spatially, ET changes varied significantly, with maximum increases of 6.11 $\mathrm{mm \cdot a^{-1}}$ in marginal areas and maximum decreases of -5.57 $\mathrm{mm \cdot a^{-1}}$ in the west [Figure 5: see original paper]. Overall, 83.3% of the region showed increasing ET trends, with 72.5% significantly increasing. E showed decreasing trends in -4.43 to 2.86 $\mathrm{mm \cdot a^{-1}}$ ranges, with 57.6% of the region decreasing and 20.2% significantly decreasing, mainly in northwestern areas with sparse vegetation. T showed increasing trends in 83.80% of the region, with 84.14% significantly increasing. The T/ET ratio increased overall, with 64.8% of the region showing significant changes, decreasing only in southwestern and eastern local areas.

Factors Influencing ET Component Changes Bayesian SEM results for T and E showed good model fit ($\hat{R} = 1.00$), revealing distinct environmental influences on ET components [Figure 6: see original paper]. For transpiration (T), LAI had the strongest direct effect (path coefficient 0.90), followed by VPD

(0.75), both significant. Pre showed weaker positive effects (0.42), while Tem and SM showed negative effects, with SM' s negative effect being smallest. In total effects [Figure 7: see original paper], LAI still dominated T (0.90), exceeding other factors. Pre' s total effect on T (0.38) was reduced due to VPD' s negative indirect effect (-0.04). For soil evaporation (E), LAI significantly inhibited E (direct effect -0.65), while Tem and SM also showed negative effects, with SM' s effect being weak (-0.08). VPD and Pre were the main positive factors (0.42 and 0.40, respectively). Except for Pre, all factors showed consistent indirect and direct effect directions. Pre' s indirect negative effect was smaller than its direct positive effect, maintaining a positive total effect as the main promoter of E. Tem was the most important negative factor for E (total effect -0.748).

The T/ET ratio reflects vegetation' s key role in terrestrial ecosystem water use, with higher values indicating greater water allocation to vegetation growth. SEM results showed Tem as the main positive factor (total effect 1.68), while VPD and Pre were main negative factors (total effects -0.90 and -0.85, respectively) [Figure 8: see original paper]. VPD generated negative indirect effects through LAI (-0.33) and SM (-0.15), while Pre generated negative indirect effects through LAI (-0.40) and SM (-0.12), though their direct effects dominated, determining the total effect direction.

Changes in Available Water To explore changes in terrestrial total available water (WA) under increasing ET, we calculated WA as the difference between precipitation and actual ET based on water balance principles. At interannual scales, WA showed an initial increase followed by decrease, growing at 0.43 $\text{mm} \cdot \text{a}^{-1}$ from 2000-2013, then decreasing at -3.78 $\text{mm} \cdot \text{a}^{-1}$. Pre decreased significantly at -71.00 $\text{mm} \cdot \text{a}^{-1}$ ($p < 0.05$), while ET increased at 0.0057 $\text{mm} \cdot \text{a}^{-1}$ ($p < 0.05$), indicating a continuously decreasing proportion of precipitation converted to available water resources. WA showed strong positive correlation with Pre. Linear regression revealed a precipitation threshold of approximately 287.42 mm for WA; years below this threshold (e.g., 2015 with 264.35 mm) experienced deficits, while others remained surplus.

Spatially [Figure 9: see original paper], WA changes showed clear patterns: overall increase in southwest and decrease in northeast, with an average change rate of -2.18 $\text{mm} \cdot \text{a}^{-1}$ (range: -12.92 to 5.40 $\text{mm} \cdot \text{a}^{-1}$). About 81.78% of the region showed decreasing WA, with 16.63% significantly decreasing, mainly in the eastern region where ET increased significantly and Pre decreased. These results indicate that regional available water resources have decreased in recent years, primarily due to the combined effects of reduced precipitation and increased ET.

Discussion

Spatiotemporal Changes in ET and Its Components This study reveals that from 2000–2023, ET in the Qilian Mountains increased significantly at 1.58 mm · a^{-1}, with T increasing at 1.79 mm · a^{-1} while E decreased at −0.21 mm · a^{-1}. The T/ET ratio increased at 0.004 a^{-1}, indicating a shift toward transpiration-dominated water use and improved water resource effectiveness. Although increased vegetation cover can suppress soil evaporation by reducing surface solar radiation, E' s reduction is far less than T' s increase, resulting in net ET growth. This aligns with studies in the Loess Plateau and ecological restoration areas, confirming that vegetation greening is a key driver of ET component changes.

Spatially, ET increased significantly in central and eastern areas but decreased in the west, likely related to regional hydrothermal configurations and vegetation distribution gradients. More critically, T' s continuous rise may represent a transition from physically-dominated evaporation to vegetation-dominated transpiration in the Qilian Mountains. While this confirms ecological restoration progress, total ET increase may intensify regional water pressure, particularly in water-limited western areas. All environmental factors mediate ET component changes through vegetation growth, confirming vegetation' s key role in water resource allocation. However, vegetation dynamics are themselves regulated by climate, and this study did not separate individual driving effects, which should be addressed in future research coupling climate-vegetation feedback models.

Water Resource Availability and Effectiveness in the Qilian Mountains Our analysis reveals distinct dominant factors for ET components, jointly regulated by climate factors and vegetation dynamics. Precipitation, as the main driver of ET in northwest China, demonstrates the fundamental role of water supply. Notably, LAI is the primary factor for T increase (total effect 0.90), indicating vegetation greening is a crucial driver of transpiration changes, consistent with studies across China. Although VPD' s total effect on E is positive, temperature, precipitation, and soil moisture enhance vegetation root development and canopy closure, indirectly suppressing E and causing its net reduction.

The T/ET ratio is most responsive to temperature (total effect 1.68), which also dominates E (total effect -0.748). Different ecosystems show varied T/ET characteristics and driving mechanisms due to differences in vegetation structure and ecological functions. In grassland and cropland ecosystems, temperature is the main positive factor for T/ET, while in forest ecosystems, both temperature (1.68) and soil moisture (-0.85) drive T/ET changes. These differences further demonstrate region-specific vegetation adaptation strategies.

Vegetation restoration measures alter ET spatial distribution and affect water resources. While previous studies suggested vegetation greening negatively impacts regional water resources, our findings show that vegetation greening intensifies water consumption while simultaneously improving effectiveness, proving its complex effects. The precipitation threshold for WA (287.42 mm) is higher than the 2015 precipitation (264.35 mm), suggesting that vegetation effectiveness improvements may depend on glacier and snowmelt water. However, this trend may not be sustainable under long-term precipitation reduction, potentially weakening water cycles and exacerbating shortages. Different ecosystem responses further highlight the need for strengthened monitoring and rational planning of greening scales to avoid excessive water consumption and achieve sustainable balance between ecological benefits and water resources.

Conclusions

Taking the Qilian Mountains as a case study, this research systematically analyzed the evolution of water resource effectiveness (T/ET, T/Pre) and availability (WA, WA/Pre) by decomposing and attributing water balance components. The main conclusions are:

1. From 2000–2023, ET and T increased significantly at 1.58 $mm \cdot a^{-1}$ and 1.79 $mm \cdot a^{-1}$, respectively, while E decreased at -0.21 $mm \cdot a^{-1}$. The T/ET ratio increased at 0.004 a^{-1}, indicating a regional shift toward transpiration-dominated water use.

2. Precipitation is the dominant factor for ET variation, while LAI is the key driver for T increase (total effect 0.90). Temperature is the primary factor affecting the T/ET ratio (total effect 1.68) and E (total effect -0.748). Vegetation restoration enhances water resource effectiveness by increasing T, but decreased precipitation and increased ET jointly reduce water availability at -3.78 $mm \cdot a^{-1}$, reflecting that vegetation restoration improves water productivity while intensifying consumption pressure.

3. WA showed an initial increase followed by sustained decrease, indicating current water conditions are approaching the critical threshold for sustainable vegetation restoration. Future management should regulate the T/E ratio to synergistically improve water availability and ecological water use efficiency.

References

[1] Wang H Q, Sun B P, Yu X X, et al. The driver pattern effect connection of vegetation dynamics in the transition area between semi-humid and semi-arid northern China[J]. Catena, 2020, 194: 104713.

[2] Konapala G, Mishra A K, Wada Y. et al. Climate change will affect global water availability through compounding changes in seasonal precipitation and evaporation[J]. Nature Communications, 2020, 11(1): 3044.

[3] Zeng Z, Peng L, Piao S. Response of terrestrial evapotranspiration to Earth' s greening[J]. Current Opinion in Environmental Sustainability, 2018, 33: 9-25.

[4] Bai P, Liu X. Intercomparison and evaluation of three global high resolution evapotranspiration products across China[J]. Journal of Hydrology, 2018, 566: 743-755.

[5] Xu T, Guo Z, Xia Y, et al. Evaluation of twelve evapotranspiration products from machine learning, remote sensing and land surface models over conterminous United States[J]. Journal of Hydrology, 2019, 578: 124105.

[6] Pour S H, Wahab A K A, Shahid S, et al. Changes in reference evapotranspiration and its driving factors in peninsular Malaysia[J]. Atmospheric Research, 2020, 246: 105096.

[7] Helbig M, Waddington J M, Alekseychik P, et al. Increasing contribution of peatlands to boreal evapotranspiration in a warming climate[J]. Nature Climate Change, 2020, 10(6): 555-560.

[8] Jiang F X, Xie X H, Wang Y B, et al. Vegetation greening intensified transpiration but constrained soil evaporation on the Loess Plateau[J]. Journal of Hydrology, 2022, 614: 128514.

[9] Wang R, Li L H, Pierre G, et al. Recent increase in the observational-derived land evapotranspiration due to global warming[J]. Environmental Research Letters, 2022, 17(2): 024020.

[10] Fu J, Gong Y Q, Zheng W W, et al. Spatial-temporal variations of terrestrial evapotranspiration across China from 2000 to 2019[J]. Science of the Total Environment, 2022, 825: 153951.

[11] Sun S, Liu Y, Chen H, et al. Causes for the increases in both evapotranspiration and water yield over vegetated China' s mainland during the last two decades[J]. Agricultural and Forest Meteorology, 2022, 324(9): 109118.

[12] Hao S R, Jia X, Mu Y M, et al. Canopy greenness, atmospheric aridity, and large rain events jointly regulate evapotranspiration partitioning in a temperate semiarid shrubland[J]. Agricultural and Forest Meteorology, 2023, 333: 109425.

[13] Jung M, Reichstein M, Ciais P, et al. Recent decline in the global land evapotranspiration trend due to limited moisture supply[J]. Nature, 2010, 467(7318): 951-954.

[14] Gao S Q, Lü Y H, Jiang X H, et al. Increased precipitation and vegetation cover synergistically enhanced the availability and effectiveness of water resources in a dryland region[J]. Journal of Hydrology, 2025, 654: 132812.

[15] Cui J, Lian X, Huntingford C, et al. Global water availability boosted by vegetation-driven changes in atmospheric moisture transport[J]. Nature Geoscience, 2022, 15(12): 982-988.

[16] Yang L, Feng Q, Yin Z, et al. Regional hydrology heterogeneity and the response to climate and land surface changes in arid alpine basin, Northwest China[J]. Catena, 2020, 187: 104345.

[17] Padrón R, Gudmundsson L, Decharme B, et al. Observed changes in dry season water availability attributed to human-induced climate change[J]. Nature Geoscience, 2020, 13(7): 477-481.

[18] Xu H J, Zhao C Y, Wang X P, et al. Spatiotemporal differentiation of the terrestrial gross primary production response to climate constraints in a dryland mountain ecosystem of northwestern China[J]. Agricultural and Forest Meteorology, 2019, 276-277: 107628.

[19] Yang Y, Roderick M L, Guo H, et al. Evapotranspiration on a greening Earth[J]. Nature Reviews Earth & Environment, 2023, 4: 626-641.

[20] Zhou D, Hao L, Kim J B, et al. Potential impacts of climate change on vegetation dynamics and ecosystem function in a mountain watershed on the Qinghai-Xizang plateau[J]. Climatic Change, 2019, 156(1): 31-50.

[21] Wu Jingjing, Jiao Liang, Zhang Hua, et al. Vegetation coverage variation in the Qilian Mountains before and after ecological restoration[J]. Acta Ecologica Sinica, 2023, 43(1): 408-418.

[22] Zhuang J C, Li Y Z, Bai P, et al. Changed evapotranspiration and its components induced by greening vegetation in the Three Rivers Source of the Tibetan Plateau[J]. Journal of Hydrology, 2024, 633: 130970.

[23] Xu H J, Zhao C Y, Wang X P. Elevational differences in the net primary productivity response to climate constraints in a dryland mountain ecosystem of northwestern China[J]. Land Degradation & Development, 2020, 31(15): 2087-2103.

[24] Yao Z, Zhao C, Yang K, et al. Alpine grassland degradation in the Qilian Mountains, China—A case study in Damaying Grassland[J]. Catena, 2016, 137: 494-500.

[25] Kayiranga A, Chen B, Guo L, et al. Spatiotemporal variations of forest ecohydrological characteristics in the Lancang-Mekong region during 1992-2016 and 2020-2099 under different climate scenarios[J]. Agricultural and Forest Meteorology, 2021, 310: 108662.

[26] Ma Y R, Guan Q Y, Sun Y F, et al. Three-dimensional dynamic characteristics of vegetation and its response to climatic factors in the Qilian Mountains[J]. Catena, 2022, 208: 105694.

[27] Miralles D G, Holmes T R H, De Jeu R A M, et al. Global land-surface evaporation estimated from satellite-based observations[J]. Hydrology and Earth System Sciences, 2011, 15(2): 453-469.

[28] Miralles D G, Bonte O, Koppa A, et al. GLEAM4: Global land evaporation and soil moisture dataset at 0.1° resolution from 1980 to near present[J].

Scientific Data, 2025, 12(1): 416.

[29] Yu K X, Liu J, Zhang X, et al. Evapotranspiration fusion and attribution analysis in the upper and middle reaches of the Yellow River Basin[J]. Journal of Hydrology: Regional Studies, 2024, 53: 101112.

[30] Muñoz Sabater J. ERA5-Land Monthly Averaged Data from 1950 to Present. Copernicus Climate Change Service (C3S) Climate Data Store (CDS)[DB/OL]. 2019. doi:10.24381/cds.68d2bb30.

[31] Chen C, Park T, Wang X, et al. China and India lead in greening of the world through land use management[J]. Nature Sustainability, 2019, 2(2): 122-129.

[32] Piao S, Wang X, Park T, et al. Characteristics, drivers and feedbacks of global greening[J]. Nature Reviews Earth & Environment, 2020, 1(1): 14-27.

[33] Myneni R, Knyazikhin Y, Park T. MODIS/Terra Leaf Area Index/FPAR 8-Day L4 Global 500 m SIN Grid V061. NASA EOSDIS Land Processes Distributed Active Archive Center (DAAC)[DB/OL]. 2021.

[34] Yang J, Huang X. The 30 m annual land cover datasets and its dynamics in China from 1985 to 2023[J]. Earth System Science Data, 2024, 13: 3907-3925.

[35] Xu Xinliang, Liu Jiyuan, Zhang Zengxiang, et al. Content and development of a 5-year interval spatial distribution dataset of terrestrial ecosystems in China (1990-2010)[J]. Journal of Global Change Data & Discovery, 2017, 1(1): 52-59.

[36] Li P, Wang J, Liu M, et al. Spatio-temporal variation characteristics of NDVI and its response to climate on the Loess Plateau from 1985 to 2015[J]. Catena, 2021, 203: 1105331.

[37] Chen Y, Lu H, Li J, et al. Effects of land use/cover change on carbon emissions and ecosystem services in Chengyu Urban Agglomeration, China[J]. Stochastic Environmental Research and Risk Assessment, 2020, 34(8): 1197-1215.

[38] Sen P K. Estimates of the regression coefficient based on Kendall’ s tau[J]. Journal of the American Statistical Association, 1968, 63(324): 1379-1389.

[39] Liu H, Gong P, Wang J, et al. Annual dynamics of global land cover and its long-term changes from 1982 to 2015[J]. Earth System Science Data, 2020, 12(2): 1217-1243.

[40] Wang Dianlai, Liu Wenping, Huang Xinyuan. Trend analysis in vegetation cover in Beijing based on Sen+Mann-Kendall method[J]. Computer Engineering and Applications, 2013, 49(5): 13-17.

[41] Ali R, Kuriqi A, Abubaker S, et al. Long-term trends and seasonality detection of the observed flow in Yangtze River using Mann-Kendall and Sen’ s innovative trend method[J]. Water, 2019, 11(9): 1855.

[42] Yang L, Shen F X, Zhang L, et al. Quantifying influences of natural and anthropogenic factors on vegetation changes using structural equation modeling: A case study in Jiangsu Province, China[J]. Journal of Cleaner Production, 2021, 280: 124330.

[43] Ye Q J, Li Z W, Duan L X, et al. Decoupling the influence of vegetation and climate on intra-annual variability in runoff in Karst Watersheds[J]. Science of the Total Environment, 2022, 824: 153874.

[44] Conradi T, Van Meerbeek K, Ordonez A, et al. Biogeographic historical legacies in the net primary productivity of Northern Hemisphere forests[J]. Ecology Letters, 2020, 23(5): 800-810.

[45] Wang Z J, Li J Z, Hou J Z, et al. Enhanced evapotranspiration induced by vegetation restoration may pose water resource risks under climate change in the Yellow River Basin[J]. Ecological Indicators, 2024, 162: 112060.

[46] Xu Yongkang, Zuo Depeng, Han Yuna, et al. Estimation of evapotranspiration in the Loess Plateau based on the TSEB model and its response to climate change and ecological restoration[J/OL]. Water Resources Protection, 1-16. [2025-7-16].

[47] Shao R, Zhang B, He X, et al. Historical water storage changes over China's Loess Plateau[J]. Water Resources Research, 2021, 57: 1-20.

[48] Yang X, Sun W, X Mu, et al. Runoff affected by climate and anthropogenic changes in a large semi-arid river basin[J]. Hydrological Processes, 2020, 34(8): 1906-191.

[49] Zhu Z, Piao S, Myneni R B, et al. Greening of the earth and its drivers[J]. Nature Climate Change, 2016, 6(8): 791-795.

[50] Lu T W, Han Y, Deng X M, et al. Vegetation influence level on the water resources effectiveness over China[J]. Environmental Research Letters, 2025, 20(3): 034058.

[51] Bai P, Liu X, Zhang Y, et al. Assessing the impacts of vegetation greenness change on evapotranspiration and water yield in China[J]. Water Resources Research, 2020, 56(10): e2019WR027019.

[52] Hoek van Dijke A J, Herold M, Mallick K, et al. Shifts in regional water availability due to global tree restoration[J]. Nature Geoscience, 2022, 15(5): 363-368.

[53] Xue Y, Liang H, Zhang B, et al. Vegetation restoration dominated the variation of water use efficiency in China[J]. Journal of Hydrology, 2022, 612: 128257.

[54] Feng X, Fu B, Piao S, et al. Revegetation in China' s Loess Plateau is approaching sustainable water resource limits[J]. Nature Climate Change, 2016, 6(11): 1019-1022.

[55] Zhou S, Williams A P, Lintner B R, et al. Soil moisture-atmosphere feedbacks mitigate declining water availability in drylands[J]. Nature Climate Change, 2021, 11(1): 38-44.

[56] Schumacher D, Keune J, Dirmeyer P, et al. Drought self-propagation in drylands due to land-atmosphere feedbacks[J]. Nature Geoscience, 2022, 15(4): 262-268.

[57] Chen J Z, Xue X Y, Du W T, et al. Short communication: Extreme glacier mass loss triggered by high temperature and drought during hydrological year 2022/2023 in Qilian Mountains[J]. Research in Cold and Arid Regions, 2024, 16(1): 1-4.

[58] Zhang C, Long D, Liu T, et al. Grassland greening and water resource availability may coexist in a warming climate in Northern China and the Tibetan Plateau[J]. Earth' s Future, 2023, 11(2): e2023EF004037.

[59] Stoy P C, El Madany T S, Fisher J B, et al. Reviews and syntheses: Turning the challenges of partitioning ecosystem evaporation and transpiration into opportunities[J]. Biogeosciences, 2019, 16(19): 3747-3775.

[60] Zu Qianxue, Ma Aoge, Sun Shanlei, et al. Causes for spatiotemporal changes in evapotranspiration and its components over the Yangtze River Basin based on the BEPS model[J]. Acta Ecologica Sinica, 2025, 45(11): 5466-5480.

[61] Yu Tengfei, Han Tuo, Xi Haiyang, et al. Cropland evapotranspiration, shelter forest transpiration and the determining factors in the middle Heihe River Basin, China[J]. Chinese Journal of Applied Ecology, 2025, 36(9): 2815-2826.

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