Dynamics of Water Use Efficiency and Its Response to Drought and Land Surface Temperature on the Loess Plateau: Postprint

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Abstract

The Loess Plateau is the region with the most severe soil erosion in the world and the largest greening magnitude in China. Studying the spatiotemporal evolution of water use efficiency (WUE) and its relationship with drought and land surface temperature (LST) in this region has become an important reference for selecting the maximum vegetation carrying threshold of the Loess Plateau. Based on the Theil-Sen trend method and the first-order difference relative contribution method, we analyzed the spatiotemporal variation patterns of WUE in different seasons and the contribution of drought and LST to WUE changes on the Loess Plateau from 2001 to 2021. The results show that: (1) From 2001 to 2021, the average WUE in spring and autumn on the Loess Plateau was less than 2.0 g C · m-2 · mm-1, while the average WUE in summer was greater than 2.0 g C · m-2 · mm-1. In spring and autumn, WUE in cropland and forestland areas was higher than that in grassland areas; in summer, WUE in cropland areas was the lowest, followed by forestland areas, and grassland areas had the highest WUE. (2) In spring and summer, WUE was dominated by a stable and unchanged trend, with spatial distribution characterized by "decrease in the central region, stable and unchanged in the western and eastern regions" ; the decreasing rate of WUE in grassland areas > forestland areas > cropland areas; in autumn, WUE was dominated by an increasing trend, with the increasing rate of WUE in grassland areas > forestland areas > cropland areas, and the spatial distribution showed a pattern of "increase in the northwest, decrease in the southeast" . (3) In spring and summer, LST had a positive contribution to WUE changes, most significantly in grassland areas; in autumn, LST had a negative contribution to WUE in grassland and forestland areas, but a positive contribution to WUE in cropland areas. Drought had a positive contribution to WUE changes in spring and autumn, and a negative contribution in summer. These results help to understand the relationship between drought, LST, and

water resources on the Loess Plateau under the background of climate change and ecological restoration project implementation.

Full Text

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Abstract

The Loess Plateau represents both the most severely soil-eroded region globally and the area with the largest greening magnitude in China. Investigating the spatiotemporal dynamics of water use efficiency (WUE) and its relationship with drought and land surface temperature (LST) has become a critical reference for determining the maximum vegetation carrying threshold in this region. Based on MODIS data from 2001 to 2021, this study employs the Theil-Sen trend method and first-order differencing relative contribution analysis to examine seasonal WUE patterns and quantify the contributions of drought and LST to WUE variations across the Loess Plateau. The results demonstrate that: (1) The multi-year average WUE values in spring and autumn are below 2.0 g $\mathrm{C \cdot m^{-1}}$, whereas summer WUE exceeds 2.0 g $\mathrm{C \cdot m^{-1}}$. Spatially, spring and autumn WUE is higher in cultivated land and forest areas compared to grassland regions, while summer WUE is lowest in cultivated land, intermediate in forest areas, and highest in grassland. (2) During spring and summer, WUE remains predominantly stable, exhibiting a spatial pattern characterized by "reduction in the central region, stability in the western and eastern regions." The declining rate of WUE is most pronounced in grassland areas, followed by forest and cultivated land areas. In autumn, WUE shows an overall increasing trend, with grassland areas displaying a higher rate of increase than forest and cultivated land areas, following a "northwest increase, southeast decrease" spatial distribution. (3) LST contributes positively to WUE changes in spring and summer, with the most significant effects observed in grassland areas. In autumn, LST negatively affects WUE in grassland and forest areas but positively influences WUE in cultivated land areas. Drought exhibits positive contributions to WUE in spring and autumn, while showing negative contributions in summer. These findings enhance understanding of the complex interactions between climate change, ecological restoration, drought, LST, and water resources on the Loess Plateau.

Keywords: water use efficiency; drought; land surface temperature; Loess Plateau

1.1 Study Area Overview

The Loess Plateau (34.7°-41.3°N, 100.8°-114.6°E) spans an area of 6.49$×10^{5}$ km^{2} across Qinghai, Gansu, Ningxia, Inner Mongolia, Shaanxi, Shanxi, and Henan provinces. The region comprises the Shanxi Plateau, Shaanxi-Gansu-Shanxi Plateau, Longzhong Plateau, Ordos Plateau, and Hetao Plain. Characterized by a temperate continental monsoon climate, precipitation concentrates in summer with frequent rainstorms, forming a distinct northwest-southeast precipitation gradient influenced by latitude, longitude, and topography. The mean annual temperature ranges from 3.6 to 14.3 °C, with cold winters, warm summers, and large annual and diurnal temperature variations. The soil consists primarily of loose-textured loess with collapsibility, making it highly susceptible to wind and water erosion following human disturbance. Vegetation types transition from forest, forest-steppe, steppe, desert steppe to desert from southeast to northwest, shaped by precipitation patterns. Due to its unique geographical location, topography, climate, and historical land use practices, water scarcity has persistently constrained regional socioeconomic development [Figure 1: see original paper].

1.2 Data Sources

Gross primary productivity (GPP) data were obtained from the MOD17A2 product, evapotranspiration (ET) from MOD16A2, and land surface temperature (LST) from MOD11A2, all provided by NASA at 500 m spatial resolution for the period 2001-2021. The MOD16A2 ET product is calculated using the Penman-Monteith equation based on meteorological reanalysis data, land cover, leaf area index, and albedo. LST data are provided in Kelvin at 1000 m resolution. Previous validation studies have confirmed that these MODIS products, despite some regional overestimation or underestimation, meet the accuracy requirements for large-scale studies. The maximum value compositing method was applied to monthly data to eliminate anomalies caused by clouds and atmospheric interference.

Meteorological data, including monthly gridded precipitation and temperature from 2001 to 2021, were acquired from the China Meteorological Administration (https://data.cma.cn). These data were used to calculate the Standardized Precipitation Evapotranspiration Index (SPEI) at 1-month and 3-month scales, reflecting seasonal drought characteristics. Land use data were derived from the 30 m annual land cover dataset developed by Yang and Huang using Landsat imagery and random forest classification, achieving overall accuracy exceeding

85% for cultivated land and 80% for other land use types .

1.3.1 WUE Calculation Water use efficiency was calculated as the ratio of GPP to ET (WUE = GPP/ET), with units of g C • m^{-1}.

1.3.2 Trend Analysis The Theil-Sen slope method, a robust non-parametric trend calculation approach insensitive to measurement errors and outliers, was employed to analyze overall WUE trends during spring, summer, and autumn from 2001 to 2021. The Mann-Kendall test assessed trend significance. The Theil-Sen slope (β) is calculated as:

$$\beta = \text{Median}\left(\frac{x_j - x_i}{j - i}\right) \quad \text{for } i < j$$

where β represents the pixel-wise WUE trend, and x and x are WUE values at times i and j, respectively. Positive β values indicate increasing trends, while negative values indicate decreasing trends.

1.3.3 First-Order Differencing Relative Contribution Method First-order differencing quantifies the relative contribution of individual or combined factors by establishing detrended relationships that reduce long-term trend effects from other influences. This method was applied to assess LST and SPEI contributions to WUE changes. First, a regression model was established:

$$Y = A \times i + B$$

where Y represents WUE, i is the year, A is the regression slope, and B is the intercept. To isolate individual and combined effects, first differences were calculated (ΔY = Y $_{1}$ - Y), representing year-to-year WUE changes. These were incorporated into a multiple regression model:

$$\Delta Y = a \times \Delta \text{SPEI} + b \times \Delta \text{LST}$$

where ΔY is the first difference of WUE, ΔSPEI is the first difference of SPEI, and ΔLST is the first difference of LST. The coefficients a and b represent the responses of WUE to SPEI and LST, respectively. Relative contributions were calculated as:

$$\text{RC}_{\text{LST}} = \frac{b \times \Delta \text{LST}}{\Delta Y} \times 100\%$$

$$\text{RC}_{\text{SPEI}} = \frac{a \times \Delta \text{SPEI}}{\Delta Y} \times 100\%$$

where RC and RC denote the relative contributions of LST and SPEI to WUE changes, respectively.

2.1 Spatial Variation Characteristics of WUE on the Loess Plateau

The spatial distribution of multi-year average WUE during 2001-2021 reveals distinct seasonal patterns [Figure 2: see original paper]. In spring, WUE exhibits a "high in northwest and southeast, low in southwest and northeast" pattern, with values above 1.8 g $C \cdot m^{-1}$ concentrated in Henan, southern Shanxi, southern Shaanxi, and northern Inner Mongolia, primarily in cultivated and forest lands. Low-value areas ($<$1.2 g $C \cdot m^{-1}$) occur in western Qinghai, western Gansu, southern Ningxia, and western Shaanxi, dominated by grassland. Summer WUE shows a "high north, low south" distribution, with most areas exceeding 1.5 g $C \cdot m^{-1}$ except for scattered low-value regions in northern and southern Qinghai. Autumn WUE displays a "high northwest, low southeast" pattern, with high values ($>$1.5 g $C \cdot m^{-1}$) in Henan, Shanxi, and Shaanxi, and low values ($<$0.9 g $C \cdot m^{-1}$) in Qinghai, Gansu, and Ningxia.

Statistical analysis by land use type shows that summer WUE averages exceed 2.0 g $C \cdot m^{-1}$ across all categories, while spring and autumn averages range between 1.4–2.0 g $C \cdot m^{-1}$ [Figure 3: see original paper]. Grassland WUE is lower than forest and cultivated land in spring and autumn but highest in summer. Cultivated land WUE is lowest in summer due to increased ET from higher temperatures, despite elevated GPP from irrigation and management practices. Forest areas, with relatively humid conditions, maintain moderate WUE values across seasons.

2.2 Trend Characteristics of WUE Changes on the Loess Plateau

Trend analysis reveals that spring WUE remained predominantly stable during 2001-2021 (60.7% of area), with decreasing trends (39.09%) exceeding increasing trends (0.07%). The spatial pattern shows "central reduction with western and eastern stability" [Figure 4: see original paper]. Slight decreases occur in western Inner Mongolia, eastern Gansu, and southern/eastern Shanxi, while significant decreases (1.41%) appear sporadically in northern Inner Mongolia. All land use types show negative trends in spring, with grassland declining fastest (0.0219 g $C \cdot m^{-1} \cdot yr^{-1}$), followed by forest (0.0189 g $C \cdot m^{-1} \cdot yr^{-1}$) and cultivated land (0.0152 g $C \cdot m^{-1} \cdot yr^{-1}$).

Summer WUE also remains stable overall (52.41% of area), with decreasing trends (41.86%) surpassing increasing trends (5.73%). The decline rate accelerates compared to spring, with grassland showing the most rapid decrease (0.0613 g $C \cdot m^{-1} \cdot yr^{-1}$), followed by forest (0.0542 g $C \cdot m^{-1} \cdot yr^{-1}$) and cultivated land (0.0432 g $C \cdot m^{-1} \cdot yr^{-1}$). In contrast, autumn WUE shows an increasing trend (52.31% of area), with stable (22.54%) and decreasing (25.05%) areas comprising the remainder. The spatial distribution follows a "northwest increase, southeast decrease" pattern, with decreases concentrated in eastern Shanxi, southeastern

Gansu, southern Shaanxi, and Henan. All land use types exhibit positive trends in autumn, with grassland increasing fastest (0.0059 g $C \cdot m^{-1} \cdot yr^{-1}$), followed by forest (0.0047 g $C \cdot m^{-1} \cdot yr^{-1}$) and cultivated land (0.0004 g $C \cdot m^{-1} \cdot yr^{-1}$).

2.3 Contributions of LST and SPEI to WUE Changes

The relative contributions of LST and SPEI to WUE variations were quantified using first-order differencing [FIGURE:5, TABLE:2]. In spring, LST contributes positively to WUE across 78.84% of the region, with negative contributions (21.16%) concentrated in Qinghai, Gansu, Henan, southern Shaanxi, and eastern Shanxi. Positive contributions dominate in northern Inner Mongolia and Ningxia. Conversely, SPEI shows predominantly negative contributions (73.38%), indicating that increasing drought severity enhances WUE. Positive SPEI contributions (26.62%) occur mainly in southern Inner Mongolia, northern Ningxia, northern Shanxi, and central Shaanxi.

Summer LST contributions are balanced, with positive (46.72%) and negative (53.28%) areas nearly equal, though negative contributions dominate in Qinghai, Gansu, Shanxi, Ningxia, and southern Shaanxi. The contribution magnitude exceeds that of spring. Summer SPEI shows positive contributions across 59.45% of the region, particularly in Henan, Ningxia, Shanxi, southern/central Shaanxi, and eastern/southern Gansu. Negative contributions (40.55%) appear in northern Shanxi, Shaanxi, and Inner Mongolia.

In autumn, LST contributions are predominantly negative (55.56%), with positive contributions (44.44%) nearly equal. Negative contributions concentrate in Shaanxi, Shanxi, central Inner Mongolia, and southern Ningxia, while positive contributions appear in Qinghai, northern Gansu, northern Ningxia, and western Inner Mongolia. Autumn SPEI shows negative contributions across 80.25% of the region, with positive contributions (9.33%) scattered in southern Gansu, Shaanxi, and southern/central Shanxi.

The combined contributions of LST and SPEI reveal that spring and autumn drought increases enhance WUE, while summer drought reduces WUE [FIGURE:6, TABLE:3]. LST positively contributes to WUE changes in spring and summer, particularly in grassland areas, but negatively affects WUE in autumn for grassland and forest areas while positively influencing cultivated land.

2.4 Contributions of LST and SPEI to WUE Changes by Land Use Type

Analysis by land use type shows that LST contributes positively to WUE in grassland and forest areas during spring and autumn, but negatively in cultivated land during spring . Across all seasons, LST positively affects WUE in grassland more strongly than in forest or cultivated land. SPEI exhibits negative contributions in spring and autumn across all land use types, indicating drought enhancement increases WUE, while showing positive contributions in summer, indicating drought reduces WUE. The contribution of WUE changes to grassland is most significant in spring, while the contribution to forest and cultivated land is greater in spring than in summer or autumn.

3.1 Spatiotemporal Analysis of WUE

The Loess Plateau has implemented extensive ecological restoration projects, particularly the Grain-for-Green program, significantly increasing vegetation coverage and carbon sequestration capacity while improving the ecological environment. However, research indicates that current artificial vegetation coverage may be approaching the region’ s soil water carrying capacity, potentially reducing the maximum vegetation restoration threshold. This study’ s analysis of WUE spatiotemporal evolution from 2001 to 2021 reveals that average WUE values in spring and autumn are below $2.0\ \mathrm{g\ C \cdot m^{-1}}$, while summer values exceed this threshold. Seasonal and land-use variations in WUE reflect different water use strategies and root characteristics. Forests with deep root systems can access middle and deep soil moisture, while grasslands rely primarily on surface soil water, making them more sensitive to climate fluctuations and human disturbance. The “northwest increase, southeast decrease” pattern in autumn WUE may relate to increased precipitation in the northwest and favorable temperature conditions in the east.

3.2 Analysis of Drought and LST Contributions to WUE

WUE changes represent a cyclical, continuous dynamic process influenced by multiple interacting factors. Drought events, characterized by their abruptness, persistence, and destructiveness, can significantly impact terrestrial ecosystem structure, composition, function, and carbon cycling, thereby altering vegetation WUE. In spring, most vegetation is dormant or reviving, with low coverage. Wind erosion affects the Loess Plateau, and increasing drought reduces vegetation growth and biomass while increasing mortality, leading to soil desiccation and reduced water retention. However, in water-limited regions, vegetation with strong drought resistance may exhibit increased WUE under severe drought due to reduced stomatal conductance and lower water requirements.

Summer drought reduces WUE on the Loess Plateau, likely because hot, stormy weather increases potential evapotranspiration while limited precipitation and low frequency provide insufficient soil moisture for carbon synthesis, reducing vegetation greenness and causing leaf shrinkage. This may also relate to increased atmospheric CO_2 concentrations and weakened East Asian summer monsoon intensity. The positive relationship between drought and WUE in spring/autumn and negative relationship in summer highlights seasonal differences in vegetation water use strategies and drought response mechanisms across land cover types.

4 Conclusions

This study investigated the spatiotemporal dynamics of water use efficiency and its responses to drought and land surface temperature on the Loess Plateau from 2001 to 2021. The main conclusions are:

1) The multi-year average WUE shows a "north-high, south-low" distribution in summer, with values exceeding 2.0 g $C \cdot m^{-1}$. Spring and autumn WUE displays a "high in northwest and southeast, low in southwest and northeast" pattern, while autumn WUE exhibits a "high northwest, low southeast"distribution. In spring and autumn, WUE is higher in cultivated land and forest areas than in grassland, whereas summer WUE is lowest in cultivated land, intermediate in forest, and highest in grassland.
2) Spring and summer WUE remains predominantly stable, with a spatial pattern of "central reduction, western and eastern stability." The declining rate is fastest in grassland, followed by forest and cultivated land. Autumn WUE shows an increasing trend, with a higher increase rate in grassland than in forest and cultivated land, following a "northwest increase, southeast decrease" spatial pattern.
3) LST positively contributes to WUE changes in spring and summer, most significantly in grassland areas. In autumn, LST negatively affects WUE in grassland and forest areas but positively influences WUE in cultivated land areas. Drought positively contributes to WUE in spring and autumn, while negatively affecting WUE in summer. The contribution of drought to WUE changes significantly exceeds that of LST.

These findings indicate that WUE on the Loess Plateau is highly sensitive to drought, underscoring the urgent need to monitor and model WUE changes under extreme drought conditions across different land cover types to provide critical data support for determining future regional vegetation carrying capacity thresholds.

References

[1] Gao Guoming, Tian Shimin, Cao Yongtao, et al. Discussion on the issues and countermeasures of ecological conservation of the Yellow River Basin[J]. Yellow River, 2020, 42(9): 126-130.

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

[3] Wang S, Fu B J, Piao S L, et al. Reduced sediment transport in the Yellow River due to anthropogenic changes[J]. Nature Geoscience, 2016, 9(1): 38-41.

[4] Zheng H, Lin H, Zhu X J, et al. Divergent spatial responses of plant and ecosystem water use efficiency to climate and vegetation gradients in the Chi-

nese Loess Plateau[J]. Global and Planetary Change, 2019, 181: 102995, doi: 10.1016/j.gloplacha.2019.102995.

[5] Pei Tingting, Li Xiaoyan, Wu Huawu, et al. Sensitivity of vegetation water use efficiency to climate and vegetation index in Loess Plateau, China[J]. Transactions of the Chinese Society of Agricultural Engineering, 2019, 35(5): 119-125.

[6] Shao Weiwei, Yang Dawen, Sun Fubao, et al. Relationship between vegetation cover and water balance in the Loess Plateau[J]. Journal of Tsinghua University (Science and Technology Edition), 2009, 49(12): 1958-1962.

[7] Liu Xianfeng, Hu Baoyi, Ren Zhiyuan. Spatiotemporal variation of water use efficiency and its driving forces on the Loess Plateau during 2000‒2014[J]. Scientia Agricultura Sinica, 2018, 51(2): 302-314.

[8] Zhang Liangxia, Hu Zhongmin, Fan Jiangwen, et al. Advances in the spatiotemporal dynamics in ecosystem water use efficiency at regional scale[J]. Advances in Earth Science, 2014, 29(6): 691-699.

[9] Chen Lingwei. Spatiotemporal variation of water use efficiency and its responses to environmental factors in Yellow River Basin during 2001‒2020[J]. Bulletin of Soil and Water Conservation, 2022, 42(5): 222-230.

[10] Deng Y, Wang X H, Wang K, et al. Responses of vegetation greenness and carbon cycle to extreme droughts in China[J]. Agricultural and Forest Meteorology, 2021, 298-299: 108307, doi: 10.1016/j.agrformet.2020.108307.

[11] Fu B J, Wang S, Liu Y, et al. Hydrogeomorphic ecosystem responses to natural and anthropogenic changes in the Loess Plateau of China[J]. Annual Review of Earth & Planetary Sciences, 2016, 45(1): 223-243.

[12] Zhang Yongrui, Zhang Yuejun, Jin Zehui, et al. The temporal and spatial characteristics of summer drought in the Loess Plateau based on SPEI[J]. Ecology and Environmental Sciences, 2019, 28(7): 1322-1331.

[13] Zheng H, Lin H, Zhou W J, et al. Revegetation has increased ecosystem water use efficiency during 2000‒2014 in the Chinese Loess Plateau: Evidence from satellite data[J]. Ecological Indicators, 2019, 102: 507-518.

[14] Jin N, Ren W, Tao B, et al. Effects of water stress on water use efficiency of irrigated and rainfed wheat in the Loess Plateau, China[J]. Science of the Total Environment, 2018, 642: 1-11.

[15] Yang Y T, Guan H D, Batelaan O, et al. Contrasting responses of water use efficiency to drought across global terrestrial ecosystems[J]. Scientific Reports, 2016, 6: 23284, doi: 10.1038/srep23284.

[16] Piao S L, Friedlingstein P, Ciais P, et al. Changes in climate and land use have a larger direct impact than rising CO_2 on global river runoff trends[J]. Proceedings of the National Academy of Sciences, 2007, 104(39): 15242-15247.

[17] Quan Q, Zhang F Y, Tian D S, et al. Transpiration dominates ecosystem water use efficiency in response to warming in an alpine meadow[J]. Journal of Geophysical Research: Biogeosciences, 2018, 123: 453-466.

[18] Jongen M, Pereira J S, Aires L M J, et al. The effects of drought and time of precipitation on the interannual variation in ecosystem-atmosphere exchange in a Mediterranean grassland[J]. Agricultural and Forest Meteorology, 2011, 151: 595-606.

[19] Scurlock J M O, Cramer W, Olson R J, et al. Terrestrial NPP: Toward a consistent data set for global model evaluation[J]. Ecological Applications, 1999, 9(3): 913-919.

[20] Mu Q Z, Zhao M S, Running S W. Improvements to a MODIS global terrestrial evapotranspiration algorithm[J]. Remote Sensing of Environment, 2011, 115(8): 1781-1800.

[21] Yang J, Huang X. The 30 m annual land cover dataset and its dynamics in China from 1990 to 2019[J]. Earth System Science Data, 2021, 13: 3907-3925.

[22] Zhou Jing, Hu Hao, He Huijuan, et al. Spatiotemporal variation and driving factors of ecological vulnerability in the Loess Plateau of northern Shaanxi[J]. Arid Land Geography, 2023, 46(11): 1768-1777.

[23] Sen P. Estimates of the regression coefficient based on Kendall' s tau[J]. Journal of the American Statistical Association, 1968, 63: 1379-1389.

[24] Liu Jiaqi, Zhou Luhong, Xi Xiaoya. Land ecological quality and its change trend prediction in the Yellow River Basin from 2000 to 2020[J]. Arid Land Geography, 2023, 46(10): 1654-1662.

[25] Zhang T, Huang Y. Estimating the impacts of warming trends on wheat and maize in China from 1980 to 2008 based on county level data[J]. International Journal of Climatology, 2013, 33(3): 699-708.

[26] Su C H, Fu B J. Evolution of ecosystem services in the Chinese Loess Plateau under climatic and land use changes[J]. Global and Planetary Change, 2013, 101: 119-128.

[27] Zhang T, Peng J, Liang W, et al. Spatial-temporal patterns of water use efficiency and climate controls in China' s Loess Plateau during 2000–2010[J]. Science of the Total Environment, 2016, 565: 105-122.

[28] Yan S, Piao S L, Huang M T, et al. Global patterns and climate drivers of water use efficiency in terrestrial ecosystems deduced from satellite-based datasets and carbon cycle models[J]. Global Ecology and Biogeography, 2016, 25(3): 311-323.

[29] Gao Y, Zhu X J, Yu G R, et al. Water use efficiency threshold for terrestrial ecosystem carbon sequestration in China under afforestation[J]. Agricultural and Forest Meteorology, 2014, 195-196: 32-37.

[30] Liu Y B, Xiao J F, Ju W M, et al. Water use efficiency of China' s terrestrial ecosystems and responses to drought[J]. Scientific Reports, 2015, 5: 13799, doi: 10.1038/srep13799.

[31] Lian X, Piao S L, Chen A P, et al. Multifaceted characteristics of dryland aridity changes in a warming world[J]. Nature Reviews Earth & Environment, 2021, 2: 232-250.

[32] Zhao M S, Running S W. Drought-induced reduction in global terrestrial net primary production from 2000 through 2009[J]. Science, 2010, 329: 940-943.

[33] Hu Z, Yu G, Wang Q, et al. Ecosystem-level water use efficiency: A review[J]. Acta Ecologica Sinica, 2009, 29(3): 1498-1507.

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