Response of Vegetation Water Use Efficiency to Meteorological Factors in the Arid Region of Northwestern China: A Case Study of Xinjiang (Postprint)

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Date: 2023-08-01T00:00:00+00:00

Abstract

Water Use Efficiency (WUE), by linking the carbon and water cycle processes of terrestrial ecosystems, has become an important indicator for understanding the response of vegetation ecosystems to climate change. Combining remote sensing imagery and reanalysis data products from 1990-2020, Net Primary Productivity (NPP) and actual Evapotranspiration (ET) were retrieved based on the Carnegie-Ames-Stanford Approach (CASA) model to systematically analyze the spatiotemporal variation patterns of vegetation WUE in Xinjiang from 1990-2020, and to discuss and explore the driving factors influencing vegetation WUE changes. The results show that over the past 31 years, vegetation WUE in Xinjiang exhibited an overall declining trend, but with 2003 as a turning point: before the turning point it showed a fluctuating declining trend, and after that a fluctuating rising trend. Over the 31 years, the spatial pattern of vegetation WUE in Xinjiang did not change significantly, with high values concentrated in plain areas, particularly in oases and desert-oasis transition zones, and low values concentrated in mountainous areas. Through analysis, it was found that changes in vegetation WUE in Xinjiang were mainly attributable to climatic factors such as precipitation, evapotranspiration, and water vapor pressure. The research findings have reference value for screening artificial and natural vegetation structure types with rational structure, strong water-saving capacity, and high productivity, and for achieving sustainable development of vegetation construction in arid and semi-arid regions, and particularly have practical significance for ecosystem security and sustainable development of agriculture and animal husbandry in Xinjiang.

Response of Vegetation Water Use Efficiency Changes to Meteorological Factors in Arid Areas of Northwest China: A Case Study of Xinjiang

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Abstract

Water use efficiency (WUE) links the processes of carbon and water cycling in terrestrial ecosystems and serves as a crucial indicator for understanding the response of vegetated ecosystems to climate change. This study systematically analyzed the spatiotemporal patterns of vegetation WUE in Xinjiang, China from 1990 to 2020 by combining 31 years of remote sensing imagery and reanalysis data products. Using the Carnegie-Ames-Stanford Approach (CASA) model, we inverted net primary productivity (NPP) and actual evapotranspiration (ET) to discuss and explore the driving factors influencing vegetation WUE changes. The results revealed that vegetation WUE in Xinjiang exhibited an overall decreasing trend over the past 31 years, with 2003 serving as a turning point. Before this turning point, WUE showed a fluctuating downward trend, while afterward it displayed a fluctuating upward trend. The spatial pattern of vegetation WUE in Xinjiang did not change significantly, with high values concentrated in plain areas, particularly in oases and desert-oasis transition zones, while low values were concentrated in mountainous regions. Analysis demonstrated that changes in vegetation WUE in Xinjiang can be primarily attributed to climatic factors such as precipitation, evapotranspiration, and water vapor pressure. These findings provide valuable references for screening artificial and natural vegetation structural types with rational configuration, strong water conservation capacity, and high productivity, thereby contributing to the sustainable development of vegetation construction in arid and semi-arid regions. The results are particularly significant for ecosystem security and the sustainable development of agriculture and animal husbandry in Xinjiang.

Keywords: water use efficiency; net primary productivity; evapotranspiration; climate change

1. Introduction

Water use efficiency (WUE) not only reflects plant physiological processes and fitness but also serves as an important pathway for understanding how terrestrial ecosystems respond to climate change by linking ecosystem carbon and water cycles. WUE is defined as the amount of net primary productivity (or dry matter) produced by plants per unit mass of water consumed. Traditionally, WUE has been calculated using measurements of leaf net photosynthetic rate and transpiration rate obtained from flux towers and photosynthesis analyzers. However, this approach is difficult to implement at large regional scales. With advances in remote sensing technology, an increasing number of scholars have recognized the potential for monitoring WUE dynamics using remote sensing data that offer broad coverage, high timeliness, and strong continuity. This efficient and convenient method has rapidly gained widespread promotion and application.

In the context of global warming and the United Nations' guidance on energy conservation and emission reduction, the relationship between carbon and water remains unclear, making the study of the relationship between "carbon sequestration" and "water consumption" particularly important. Previous research has shown that, on the one hand, water conditions significantly influence WUE; on the other hand, elevated CO_2 concentrations (implying stronger warming trends) significantly promote NPP increases, while temperature indirectly reduces WUE by controlling evapotranspiration processes. For arid region ecosystems, the impacts of climate change factors on WUE are even more complex. With global warming, WUE may exhibit upward or downward trends with climate change, or show patterns of initial increase followed by decrease or vice versa.

The threshold values for such stage changes remain unclear. The arid region of Northwest China features a unique mountain-oasis-desert landscape, where the stability of mountain-oasis-desert ecosystems is fundamental to sustainable ecological environments in arid regions. Understanding WUE changes and conducting related driving mechanism research is crucial for ecological security and the sustainable development of agriculture and animal husbandry in this region, particularly as it faces increasingly severe water shortages. Currently, numerous studies have investigated the relationship between WUE and meteorological factors, demonstrating that climate elements are key drivers of vegetation WUE changes. For instance, Pei et al. studied the sensitivity of different vegetation types on the Loess Plateau to precipitation and temperature, finding that vegetation type is a critical factor causing sensitivity differences, with shrubs showing significantly higher sensitivity than forests and grasslands. Cui et al. discovered threshold effects in vegetation WUE responses to climate factors: when annual precipitation is <700 mm (on the Qinghai-Tibet Plateau), sensitivity to precipitation decreases with increasing precipitation, while the opposite occurs when annual precipitation >700 mm.

With massive greenhouse gas emissions, global warming has become an undeniable reality. The warming rate in Northwest China’s arid region exceeds national and global levels, which will inevitably accelerate water cycling processes and intensify drought conditions. From 1979 to 2015, Xinjiang experienced significant warming with increased frequency and intensity of extreme precipitation events. Consequently, climate change factors have complex effects on WUE. Therefore, investigating WUE changes and their driving mechanisms is of great significance for ecosystem security and sustainable agricultural and pastoral development in this region.

2. Study Area

Xinjiang is located in northwestern China (73°40 -96°23 E, 34°25 -49°10 N), far from the ocean, representing a typical arid and semi-arid region covering approximately 1.6$×10^{6}$ km^{2}. The terrain follows a “three mountains surrounding two basins” pattern, with three mountain ranges from south to north: the Kunlun Mountains, Tianshan Mountains, and Altai Mountains. These high mountains block atmospheric circulation, causing air subsidence and creating rain shadow effects that result in two vast desert basins: the Tarim Basin in the south and the Junggar Basin in the north. The region has an average annual temperature of 9.6°C and annual precipitation below 150 mm, only one-quarter of China’ s average level. The Tianshan Mountains divide Xinjiang into northern and southern parts. Northern Xinjiang has a continental arid and semi-arid climate with winter averages of -13°C and summer averages of 22.2°C, receiving 210 mm annual precipitation. Southern Xinjiang has a continental arid climate with winter averages of -5.7°C and summer averages of 24.4°C, receiving less than 100 mm annually. Due to the dry climate, evaporation is very high, with average annual evaporation of 1000–4500 mm. The melting of glaciers and snow in high mountain zones changes runoff recharge patterns, increases uncertainty in mountain runoff, reduces regional water storage, alters regional vegetation WUE conditions, and even affects vegetation habitat distribution. Therefore, understanding WUE changes is crucial for ecological security and sustainable development in Xinjiang.

[Figure 1: see original paper]

2.1 Data Sources

The data used in this study include: (1) Input parameters for the Carnegie-Ames-Stanford Approach (CASA) model to calculate net primary productivity (NPP): FPAR and NDVI parameters obtained from MODIS products (https://ladsweb.nascom.nasa.gov/search/); (2) Temperature data: obtained from GLDAS (http://ldas.gsfc.nasa.gov/gldas/); (3) Land use/cover data: obtained from the Chinese Academy of Sciences Resource and Environmental Science Data Center (http://www.resdc.cn/); (4) Digital elevation model (DEM) data: obtained from Geospatial Data Cloud (http://www.gscloud.cn/) for WUE analysis. Meteorological element data include: actual evapotranspiration (ET), saturated vapor pressure (SVP), actual vapor pressure

(AVP), and potential evapotranspiration (PET), obtained from TerraClimate (https://www.ecmwf.int), where saturated vapor pressure deficit (VPD) is the sum of SVP and AVP. Detailed information for each dataset is provided in Table 1.

2.2 Methods

2.2.1 NPP Calculation Based on the CASA model that fully considers vegetation physiological and ecological characteristics, this study accurately retrieved regional NPP dynamics by inputting readily available, timely remote sensing data. The CASA model has been widely applied in regional research and validated against measured biomass data, showing only 6.22% error in NPP estimation for Xinjiang vegetation. The main input parameters include photosynthetically active radiation absorbed by vegetation and actual light use efficiency, calculated as:

$$NPP(x,t) = APAR(x,t) \times \varepsilon(x,t)$$

where $NPP(x,t)$ is vegetation net primary productivity at pixel x in month t (g $\mathrm{C \cdot m^{-2}}$); $APAR(x,t)$ is photosynthetically active radiation absorbed by vegetation at pixel x in month t ($\mathrm{MJ \cdot m^{-2}}$); and $\varepsilon(x,t)$ is actual light use efficiency at pixel x in month t (g $\mathrm{C \cdot MJ^{-1}}$). WUE is defined as the amount of carbon assimilated into biomass or grain per unit area of plant water consumed.

2.2.2 WUE Calculation WUE is calculated as:

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

where WUE is vegetation water use efficiency (g $\mathrm{C \cdot mm^{-1}}$); NPP is vegetation net primary productivity (g $\mathrm{C \cdot m^{-2}}$); and ET is actual evapotranspiration (mm) obtained from TerraClimate reanalysis data.

2.2.3 WUE Trend Analysis Based on univariate linear regression analysis, the regression coefficient (slope) of WUE was calculated pixel by pixel at both interannual and monthly scales using:

$$Slope = \frac{n \times \sum_{j=1}^{n} (j \times P_j) - \sum_{j=1}^{n} j \times \sum_{j=1}^{n} P_j}{n \times \sum_{j=1}^{n} j^2 - (\sum_{j=1}^{n} j)^2}$$

where n is the length of the time series (31 years); j is the sample year or month; and P_j is the WUE value in year or month j. To ensure reliability, the relative root mean square error (RRMSE) between the two was used to evaluate model performance. Based on this, the study utilized CASA model-provided surface characteristic parameters.

2.2.4 Pearson Correlation Analysis Pearson correlation coefficients were used to further analyze correlations between ecosystem WUE and climate factors. This process was implemented in Matlab using:

$$r = \frac{\sum_{i=1}^{n}(X_i - \bar{X})(Y_i - \bar{Y})}{\sqrt{\sum_{i=1}^{n}(X_i - \bar{X})^2 \times \sum_{i=1}^{n}(Y_i - \bar{Y})^2}}$$

where r is the Pearson correlation coefficient; n is the time series length; X_i and Y_i are WUE values and selected climate factor values (including precipitation, temperature, ET, VPD, SVP, AVP, and PET) in year i; and $\bar{X}$ and $\bar{Y}$ are the multi-year average WUE and climate factor values, respectively.

3.1 Interannual Variation Characteristics of Vegetation WUE in Xinjiang

From 1990 to 2003, vegetation WUE in Xinjiang (both northern and southern) showed a fluctuating downward trend; after 2003, vegetation WUE exhibited a fluctuating upward trend (Figure 2). This pattern aligns with the abrupt warming and enhanced evaporation around 1997 in Xinjiang, where vegetation adjusted its ecosystem processes to better survive. The average annual WUE values for Xinjiang vegetation from 1990 to 2020 mostly ranged between 0.60–4.10 g C$\cdot$mm^{-1}, with all regions showing fluctuating downward trends. Southern Xinjiang showed the highest decreasing trend (-0.0529 g C$\cdot$mm^{-1} yr^{-1}), while northern Xinjiang showed the lowest decreasing trend (-0.0355 g C$\cdot$mm^{-1} yr^{-1}). Xinjiang' s overall decreasing trend fell between these two values (-0.0016 g C$\cdot$mm^{-1} yr^{-1}).

The study found that temporal trends differed across periods and showed opposite patterns, with 2003 serving as the turning point. Before 2003, Xinjiang vegetation WUE showed a slight decreasing trend overall (-0.0016 g C$\cdot$mm^{-1} yr^{-1}). Spatially, the area proportion of increasing regions (51.02%) was greater than decreasing regions (48.98%), with significantly increasing areas (9.17%) higher than significantly decreasing areas (7.69%). Significantly increasing regions were mainly concentrated in mountainous areas, while significantly decreasing regions were concentrated in plain oasis areas.

[Figure 2: see original paper]

3.2 Spatial Variation Characteristics of Vegetation WUE in Xinjiang

The spatial distribution of average annual WUE in Xinjiang from 1990 to 2020 showed that most values were concentrated in the range of 0–24 g C$\cdot$mm^{-1}, with regions higher than 24 g C$\cdot$mm^{-1} mainly distributed in the Kunlun Mountains at the upper reaches of the Hotan and Yarkant Rivers, the lower reaches of the Qarqan River, the Kumkuli Basin, and sporadically in other mountainous areas (Tianshan and Altai Mountains). Due to perennial drought in Xinjiang, to ensure accurate representation of regional differentiation patterns, this study limited the WUE value range to 0-24 g C・mm^{-1}.

Analysis of WUE spatial distribution images for northern and southern Xinjiang revealed that plain oasis and desert-oasis transition zones had higher WUE than mountainous areas, and lower latitude regions had higher WUE than higher latitude regions. Southern Xinjiang vegetation WUE was higher than northern Xinjiang (Figure 3). Overall, the spatial pattern of vegetation WUE in Xinjiang did not change significantly from 1990 to 2020. The study area encompassed land use types (grassland, cropland, forest, shrubland, and wetland).

[Figure 3: see original paper]

[Figure 4: see original paper]

3.3 Vertical Gradient Variation of Vegetation WUE in Xinjiang

Except for 1990-2020 when southern Xinjiang' s mountainous WUE was higher than its plain areas, both Xinjiang overall and northern Xinjiang showed higher WUE in plain areas than mountainous areas from 1990 to 2020. All mountainous and plain areas in Xinjiang and its sub-regions showed decreasing trends (Figure 5). Xinjiang' s mountainous WUE decreasing trend fell between northern and southern Xinjiang at -0.0361 g C・mm^{-1} yr^{-1}. Mountainous areas showed the highest decreasing trend in southern Xinjiang (-0.0712 g C・mm^{-1} yr^{-1}) and the lowest in northern Xinjiang (-0.0009 g C・mm^{-1} yr^{-1}). Plain areas showed the highest decreasing trend in southern Xinjiang (-0.0424 g C・mm^{-1} yr^{-1}) and the lowest in northern Xinjiang (-0.0108 g C・mm^{-1} yr^{-1}). Xinjiang' s plain area decreasing trend fell between northern and southern Xinjiang at -0.0016 g C・mm^{-1} yr^{-1}.

[Figure 5: see original paper]

3.4 Variation Characteristics of WUE for Different Vegetation Types in Xinjiang

Artificial vegetation was defined as the intersection of cropland land use type and normalized vegetation index regions, with natural vegetation areas being all vegetation areas excluding artificial vegetation. Analysis of average annual WUE and its trends from 1990 to 2020 for different vegetation types revealed that artificial vegetation WUE (2.31 g C・mm^{-2}) was higher than natural vegetation (1.23 g C・mm^{-2}). Natural vegetation mainly included forest, shrubland, wetland, and grassland, with grassland WUE at 2.84 g C・mm^{-2}, forest at 1.08 g C・mm^{-2}, shrubland at 0.56 g C・mm^{-2}, and wetland at 0.46 g C・mm^{-2} (Figure 6). The ranking of different vegetation types by WUE from high to low was: grassland, artificial vegetation, natural vegetation, forest, wetland, and shrubland. Due to precise irrigation and technical cultivation, artificial vegetation showed increased WUE values. Although natural vegetation must improve WUE to cope with harsh arid climates, its WUE remained lower than artificial vegetation. Among natural vegetation, forest and wetland environments are relatively humid with adequate water, resulting in lower WUE values. However, grassland is the dominant vegetation type in Xinjiang, located in relatively arid regions with lower WUE and higher sensitivity to climate change, requiring improved WUE to cope with harsh conditions.

Regarding trends in different vegetation types, both artificial vegetation and grassland showed negative trends. Most of the study area is grassland, and artificial vegetation (crops) is concentrated in high-latitude subalpine meadow regions (plain areas with elevation <1500 m), making it sensitive to climate change. Global warming and temperature increases have intensified drought, increased ET, and led to decreasing WUE trends in artificial vegetation and grassland. Forest, shrubland, and wetland are mostly concentrated in mountainous areas with relatively humid conditions where drought does not limit water availability but rather satisfies vegetation heat requirements. Since 2003, mountainous vegetation WUE has shown an upward trend, possibly attributable to CO_2 fertilization effects. Therefore, forest, shrubland, and wetland WUE showed increasing trends. The ranking of positive trends from high to low was: shrubland (0.0140 g $C \cdot mm^{-1}$ yr^{-1}), forest (0.0110 g $C \cdot mm^{-1}$ yr^{-1}), wetland (0.0100 g $C \cdot mm^{-1}$ yr^{-1}), and natural vegetation (0.0002 g $C \cdot mm^{-1}$ yr^{-1}). The ranking of negative trends from high to low was: grassland (-0.0340 g $C \cdot mm^{-1}$ yr^{-1}) and artificial vegetation (-0.0030 g $C \cdot mm^{-1}$ yr^{-1}) (Figure 6).

[Figure 6: see original paper]

4. Discussion

The study area focused on vegetated regions (natural and artificial vegetation areas) where vegetation can normally grow in arid and semi-arid climate zones. Regardless of natural or anthropogenic factors, this indicates that vegetated habitats in arid regions have relatively humid microclimates. From 1990 to 2020, vegetation WUE in this region showed a decreasing trend while ET showed an increasing trend. Therefore, ET played a dominant role in vegetation WUE changes in this region.

The global multi-model integrated average WUE from 1982 to 2011 was estimated at 1.65-1.83 g $C \cdot mm^{-1}$, while some researchers calculated a global average annual WUE of 2.1$±0.35gC·mm^{-1}, withdifferencesarisingfromdifferentdatasources.Studiesshow
fertilization effect increases NPP, this increase is still lower than the ET increase caused by high temperatures. Therefore, vegetation WUE in Xinjiang and its sub-regions showed a decreasing trend from 1990 to 2020.

Correlation analysis between WUE and climate factors revealed that, except for precipitation, Xinjiang vegetation WUE was negatively correlated with all other climate factors, with VPD showing the strongest negative correlation. In arid regions, VPD is the denominator in the WUE calculation and thus shows high negative correlation with WUE, further demonstrating the dominant role of ET in WUE. Since Xinjiang' s vegetated areas are generally in arid climates but have humid habitats due to altitude and human activities, WUE is less affected by precipitation. Northern and southern Xinjiang showed different patterns: northern Xinjiang vegetation WUE was positively correlated with precipitation (though weakly) and strongly negatively correlated with VPD, indicating relatively humid conditions for an arid region. Southern Xinjiang vegetation WUE was more strongly affected by VPD, while northern Xinjiang was more affected by precipitation, though both sub-regions were dominated by climate factors.

The impact of climate factors on Xinjiang vegetation WUE was relatively small, further reflecting that Xinjiang vegetation WUE is influenced not only by climate factors such as precipitation and temperature but also more significantly by mountain glacier and snow meltwater. Therefore, vegetation WUE may have temporal lag effects with climate factors, which should be considered in future research. Additionally, to more finely characterize the mechanisms of climate change impacts on WUE, it is necessary to analyze WUE responses to climate change at leaf and canopy scales.

5. Conclusions

From 1990 to 2020, vegetation WUE in Xinjiang (both northern and southern) showed the following characteristics:

1) The average annual WUE change magnitude ranged from 0.60 to 4.10 g $C \cdot mm^{-1}$, with an overall fluctuating downward trend. Southern Xinjiang showed the highest decreasing trend (-0.0529 g $C \cdot mm^{-1}$ yr^{-1}), northern Xinjiang the lowest (-0.0355 g $C \cdot mm^{-1}$ yr^{-1}), and Xinjiang overall fell between these values (-0.0016 g $C \cdot mm^{-1}$ yr^{-1}).

2) The spatial pattern remained relatively stable, with high values in plains (especially oases and desert-oasis transition zones) and low values in mountains. Plain WUE was higher than mountainous WUE, and all regions showed decreasing trends.

3) Among different vegetation types, WUE ranking from high to low was: grassland (2.84 g $C \cdot mm^{-2}$), artificial vegetation (2.31 g $C \cdot mm^{-2}$), forest (1.08 g $C \cdot mm^{-2}$), natural vegetation (1.23 g $C \cdot mm^{-2}$), wetland (0.46 g $C \cdot mm^{-2}$), and shrubland (0.56 g $C \cdot mm^{-2}$). Positive trends ranked from high to low: shrubland (0.0140 g $C \cdot mm^{-1}$ yr^{-1}), forest (0.0110 g $C \cdot mm^{-1}$ yr^{-1}), wetland (0.0100 g $C \cdot mm^{-1}$ yr^{-1}), and natural vegetation (0.0002 g $C \cdot mm^{-1}$ yr^{-1}). Negative trends ranked from high to low: grassland (-0.0340 g $C \cdot mm^{-1}$ yr^{-1}) and artificial vegetation (-0.0030 g $C \cdot mm^{-1}$ yr^{-1}).

4) Xinjiang and southern Xinjiang vegetation WUE showed strong negative correlation with VPD, while northern Xinjiang was more affected by precipitation. However, the impact of climate factors on Xinjiang vegetation WUE was relatively small, indicating that WUE is more influenced by

mountain glacier and snow meltwater than by climate factors such as precipitation and temperature.

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