Postprint: Evapotranspiration Estimation and Attribution Analysis in the Semi-arid Region of Inner Mongolia

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Abstract

Evapotranspiration (ET) represents a critical component of ecosystem water cycling, governing water and heat transfer within ecosystems. Quantifying ET and its constituent components of transpiration (T) and evaporation (E) at the regional scale, and understanding the mechanisms by which environmental factors influence them, facilitates rational utilization and allocation of water resources while providing a reference for investigating climate change impacts on regional ecosystem hydrological cycles. Based on the Boreal Ecosystem Productivity Simulator (BEPS) model, this study validates the model' s applicability in the research area, quantifies changes in ET and its components in the semi-arid region of Inner Mongolia from 1981 to 2018, and conducts attribution analysis. Results indicate that, validated against multiple datasets, BEPS model calculations accurately reflect the distribution and variation trends of ET and its components in the study area. From 1981 to 2018, the multi-year average ET for grassland, cropland, and forest in the study area was 278.22 mm, 362.50 mm, and 308.81 mm, respectively. E, T, and ET exhibited significant increasing trends over the years, with rates of 0.42 mm · a-1, 0.63 mm · a-1, and 1.05 mm · a-1, respectively. The spatial distribution patterns of ET and T were similar across the entire region, contrasting with that of E, and interannual fluctuations in ET were primarily influenced by interannual fluctuations in T. Integrating changes in influencing factors with the sensitivity of E, T, and ET to these factors reveals that T and ET in grassland and cropland, as well as ET in forest, were mainly controlled by variations in Vapor Pressure Deficit (VPD) and mean temperature (TEMP). Although Normalized difference vegetable index (NDVI) in both cropland and forest showed decreasing trends, T in the forest environment was more sensitive to NDVI changes, resulting in a greater negative contribution.

Full Text

Evapotranspiration of a Semi-Arid Landscape in Inner Mongolia: Estimation and Attribution

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Abstract

Evapotranspiration (ET) represents the most critical flux term in ecosystem water budgets, governing water and heat exchange between terrestrial ecosystems and the atmosphere. Quantifying the magnitude and dynamics of ET and its components—evaporation (E) and transpiration (T)—at regional scales, and deriving a mechanistic understanding of their underlying controls, is essential for sustainable water resource management under changing climate conditions. Using the process-based Boreal Ecosystem Productivity Simulator (BEPS) model, we estimated ET and its components in the semi-arid region of Inner Mongolia (40.16°-46.77°N, 110.33°-119.91°E) from 1981 to 2018. Model validation against multiple datasets demonstrated that BEPS accurately reproduced the spatial distribution and temporal trends of ET and its components in the study area. The multi-year average annual ET for grassland, cropland, and forest ecosystems was 278.22 mm, 362.50 mm, and 308.81 mm, respectively. Over the study period, E, T, and ET exhibited significant increasing trends at rates of 0.42 $\text{mm} \cdot \text{a}^{-1}$, 0.63 $\text{mm} \cdot \text{a}^{-1}$, and 1.05 $\text{mm} \cdot \text{a}^{-1}$, respectively.

Spatial analysis revealed that T showed distribution patterns opposite to E but similar to ET across the region. Interannual variability in ET was primarily driven by fluctuations in T. Attribution analysis, combining sensitivity coefficients with observed changes in driving factors, indicated that T and ET in grasslands and croplands, as well as ET in forests, were mainly controlled by vapor pressure deficit (VPD) and mean air temperature. Although normalized difference vegetation index (NDVI) showed decreasing trends for both cropland and forest, forest environmental T exhibited greater sensitivity to NDVI variations, resulting in stronger negative contributions compared to cropland.

Keywords: evapotranspiration; evaporation; transpiration; BEPS model; semi-arid area

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1 Introduction

1.1 Study Area

This study focuses on the Xilingol League and Ulanqab City region within the semi-arid zone of Inner Mongolia, located between 40.16°-46.77°N and 110.33°-119.91°E [Figure 1: see original paper]. The region covers approximately 28.56×10^{4} km^2 and experiences a temperate continental climate, with a multi-year average temperature of 3.12 °C and total precipitation of 314.76 mm. The dominant land cover types are grassland and cropland. Representative flux observation stations within the region include the Duolun station (42.53°N, 116.22°E) and Xilinhot station (43.53°N, 116.67°E), which conduct long-term water vapor flux measurements for model validation.

Based on land cover data, grassland, cropland, and forest accounted for 75.07%, 5.94%, and 11.67% of the study area, respectively, during 1981-2018. Vegetation cover distribution remained relatively stable, with grassland area increasing by 0.84%, forest area decreasing by 1.56%, and cropland area decreasing by 1.50%. Consequently, we focused on investigating the impacts of climate change and vegetation growth status on regional water cycling, while neglecting effects from land cover type changes.

1.2 Model Description

We employed the Boreal Ecosystem Productivity Simulator (BEPS) to simulate regional T, E, and ET. The model's key feature is its separation of canopy leaves into sunlit and shaded fractions, enabling integration of stomatal conductance and scaling of instantaneous leaf-level photochemical models (Farquhar model) to daily carbon and water fluxes [cite]. Through continuous development and validation, BEPS has proven capable of accurately estimating ecosystem ET processes and has been successfully applied across East Asia [cite] and China [cite]. The primary computational procedures are detailed in Liu et al. [cite] and Chen et al. [cite].

1.3 Data Sources

Meteorological input data were obtained from the China Meteorological Data Service Centre's daily surface climate dataset (http://data.cma.cn), including daily temperature, precipitation, relative humidity, and sunshine duration from national meteorological stations during 1981–2018. This dataset underwent rigorous quality control, including spatial and temporal consistency checks with manual verification and correction, followed by outlier removal. Given the relatively flat terrain of the study area, we interpolated station data to a 0.01° spatial resolution using the Kriging method and masked it to the study region boundary, producing a daily dataset of 958$×$662 pixels.

Leaf area index (LAI) data for 1981–2018 were derived from the GLOBMAP LAI product (1 km resolution) developed by Liu et al. [cite] at the Institute of Geographic Sciences and Natural Resources Research, Chinese Academy of Sciences. This product has been validated to achieve high accuracy [cite]. The data were resampled to 0.01° resolution and masked to match the meteorological data grid for model input.

Land cover data were obtained from the Resources and Environmental Science Data Center of the Chinese Academy of Sciences (http://www.resdc.cn), generated through manual visual interpretation of Landsat TM/ETM imagery. This dataset represents one of China' s most accurate land use remote sensing monitoring products, with six primary categories: cropland, forest, grassland, water bodies, residential land, and bare land. The 0.01° resolution data were clipped and masked for the study region as model input.

Normalized Difference Vegetation Index (NDVI), a critical parameter reflecting vegetation growth status, was obtained from GIMMS3g (http://ecocast.arc.nasa.gov/data/pub/gimms) and SPOT/VEGETATION NDVI products from the Chinese Academy of Sciences (http://www.resdc.cn). Data preprocessing included format conversion, projection transformation, mosaicking, clipping, and resampling to 0.01° resolution. Maximum value compositing was applied to generate continuous monthly NDVI data for attribution analysis of regional ET and component changes.

Validation data consisted of water vapor flux measurements from open-path eddy covariance systems at Duolun and Xilinhot stations. The 30-minute average latent heat flux was calculated as the covariance between vertical wind speed fluctuations and water vapor concentration scalars, processed using EddyPro software with outlier removal and 2D coordinate rotation. Daily ET was computed by dividing daily latent heat flux by the latent heat of vaporization ($\lambda = 2.45\ \mathrm{MJ \cdot kg^{-1}}$). Short gaps were filled using linear interpolation, while longer gaps were filled using the daily average method [cite]. Energy balance closure ratios exceeded 0.80, meeting data quality requirements [cite].

1.4 Sensitivity Analysis

We employed the sensitivity coefficient proposed by McCuen [cite], defined as the ratio of relative change in a dependent variable to relative change in an independent variable, to quantify the contribution of each factor to changes in ET components. The calculation method follows Bi et al. [cite]. Combining sensitivity coefficients with observed changes in independent variables allows comprehensive attribution of factor contributions to dependent variable changes. We selected five key factors for analysis: mean air temperature (TEMP), precipitation (PRE), vapor pressure deficit (VPD), total solar radiation (RAD), and NDVI.

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2 Results and Analysis

2.1 Model Validation

Comparison of monthly ET simulations against observations at Duolun and Xilinhot stations during 2006–2008 [Figure 2: see original paper] showed small biases of 9.62 mm and 10.14 mm, respectively. The model explained 85% of ET variability ($R^2 = 0.85$), with a relative error of 6.70% . For T simulation, the average relative error was 3.20%, while the T/ET ratio had a relative error of 1.90%, indicating high accuracy at the site scale [cite].

Spatial patterns of T, ET, and the T/ET ratio were compared with the 1981–2015 China terrestrial ecosystem T/ET dataset [cite], showing high consistency. These validations confirm that BEPS provides reasonable estimates suitable for analyzing spatiotemporal variations in E, T, and ET across the study region.

2.2 Spatiotemporal Characteristics of ET and Its Components

Based on land cover classification, we extracted grassland, cropland, and forest pixels to analyze ecosystem-specific water consumption. During 1981-2018, average annual water consumption (ET) and water yield (PRE - ET) varied substantially among land cover types . Grassland ET was 278.22 mm with water yield of 31.32 mm; cropland ET was 362.50 mm with water yield of -12.43 mm (indicating water deficit); and forest ET was 308.81 mm with water yield of 15.96 mm. Cropland showed the highest total water consumption, followed by forest and grassland.

Regional averages of E, T, and ET during 1981-2018 were 167.13 mm, 119.16 mm, and 286.35 mm, respectively. All three components exhibited significant increasing trends ($P < 0.05$) at rates of 0.42 $mm \cdot a^{-1}$, 0.63 $mm \cdot a^{-1}$, and 1.05 $mm \cdot a^{-1}$ [Figure 3: see original paper]. Compared with T, E showed smaller interannual variability, indicating that ET fluctuations were primarily driven by T variations. The T/ET ratio increased at $0.0001 \cdot a^{-1}$, suggesting a rising contribution of transpiration to total ET.

Spatial distributions revealed contrasting patterns [Figure 4: see original paper]. E decreased from northwest to southeast, with higher values in sparsely vegetated northwestern areas (>160 mm) and lower values in northeastern forests (<120 mm). Conversely, T showed low values in the northwestern grassland (<80 mm) and high values in northeastern forests and southeastern croplands (>120 mm). ET patterns resembled T, with values <275 mm in northwestern low-vegetation areas and >300 mm in southern croplands and northeastern forests.

Trend analysis [Figure 5: see original paper] showed widespread increasing E trends, particularly significant ($P < 0.05$) in northern grasslands and southern croplands with rates >1.00 $mm \cdot a^{-1}$. T increased significantly across most regions, especially in western grasslands and southern croplands (>1.00 $mm \cdot a^{-1}$), but decreased in northeastern forests (-0.78 $mm \cdot a^{-1}$). ET increased significantly throughout the region, particularly in northern grasslands and southern croplands (>1.50 $mm \cdot a^{-1}$), while decreasing insignificantly in parts of the northwest and south. The T/ET ratio increased in grasslands but decreased in croplands and forests, with forests showing the fastest decline (-0.002 $\cdot a^{-1}$).

2.3 Attribution Analysis

Changes in key driving factors during 1981–2018 are summarized in . NDVI increased regionally at 0.0004 $\cdot a^{-1}$, with grassland showing an increasing trend while cropland and forest exhibited decreasing trends (forest: -0.0004 $\cdot a^{-1}$). Mean temperature increased significantly at 0.05 °C $\cdot a^{-1}$ (regional average: 3.12 °C). Precipitation decreased regionally at -1.00 $mm \cdot a^{-1}$, with forest showing the fastest decline. VPD increased at 0.002 $kPa \cdot a^{-1}$ (regional average: 0.09 kPa). Solar radiation decreased at -0.17 $W \cdot m^{-2} \cdot a^{-1}$, with cropland showing the largest reduction.

Attribution results for E changes showed forest E had the largest relative change (15.90%). VPD was the dominant factor for E increases across all land cover types, with relative contributions of 12.22% for forest, 10.90% for grassland, and 9.38% for cropland. The ranking of factor contributions was VPD > PRE > RAD > TEMP > NDVI for grassland and cropland, and VPD > RAD > TEMP > NDVI > PRE for forest.

For T changes , cropland showed the largest relative increase (24.80%). VPD was the primary driver for T increases in cropland (19.34% contribution) and grassland (20.09%). Forest T was influenced by both VPD increase (positive) and NDVI decrease (negative), resulting in a 13.83% relative change. The dominant factor ranking was VPD > TEMP > NDVI > RAD > PRE for grassland and cropland, and VPD > NDVI > TEMP > RAD > PRE for forest.

ET changes were largest for cropland (19.10%), driven primarily by VPD (13.93% contribution). Grassland and forest ET relative changes were 13.25% and 14.64%, respectively, with factor contributions ranked as VPD > TEMP > RAD > NDVI > PRE. Regionally, the dominant factors for ET were VPD > TEMP > RAD > PRE > NDVI.

3 Discussion

Model validation against site measurements and previous studies confirmed that BEPS accurately simulated ET and its components, with relative errors of 2.10% for T, 2.30% for ET, and 1.60% for the T/ET ratio. Our simulated multi-year average ET (278.22–362.50 mm) aligns with previous estimates for Inner Mongolia using BEPS [cite], SEBS [cite], and WaVEM [cite] models, which reported ET ranges of 300–400 mm and 450 mm for different sub-regions. The consistency across multiple validation approaches demonstrates the reliability of our simulations.

The T/ET ratio is a key parameter for quantifying ecosystem water use efficiency [cite]. Previous studies indicate that T/ET correlates with vegetation status, with values of 0.33 ± 0.50 for sparse vegetation and 1.30–2.00 for well-vegetated areas [cite]. Our regional average T/ET of 0.41 falls within this expected range. The increasing T/ET trend in grasslands reflects improved vegetation growth, enhancing water use efficiency, while decreasing T/ET in croplands and forests indicates a rising proportion of E in total ET.

Diverse ecological conditions in semi-arid regions modulate ET responses to climate [cite]. In the sparsely vegetated northwestern study area, high temperatures and large VPD accelerate evaporation rates, making E the dominant process. Conversely, in the densely vegetated eastern and southern regions with higher NDVI, greater canopy roughness enhances vegetation-atmosphere moisture exchange, making T the primary pathway. The well-developed root systems in forests and croplands absorb soil water that would otherwise evaporate, further promoting transpiration. Additionally, agricultural irrigation in southern croplands may contribute to the observed ET increases.

Our attribution analysis reveals that VPD and temperature are the dominant controls on ET and its components across all land cover types. While NDVI increases enhanced grassland T and ET, decreasing NDVI in croplands and forests, particularly the rapid decline in forests ($-0.0004 \cdot a^{-1}$), negatively impacted T. The greater sensitivity of forest T to NDVI changes resulted in stronger negative contributions compared to cropland. This differential response highlights the importance of vegetation management in mitigating climate change impacts on water cycling.

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4 Conclusions

Using the BEPS model with remote sensing, meteorological, and observational data, we quantified spatiotemporal variations in E, T, and ET across the semi-arid Xilingol League and Ulanqab City region of Inner Mongolia from 1981 to 2018. The model accurately reproduced observed patterns and trends. Key findings include:

1. **Magnitude and Trends**: Multi-year average ET was 278.22 mm for

grassland, 362.50 mm for cropland, and 308.81 mm for forest. ET, T, and E increased significantly at rates of 1.05 $mm \cdot a^{-1}$, 0.63 $mm \cdot a^{-1}$, and 0.42 $mm \cdot a^{-1}$, respectively. Interannual ET variability was primarily driven by T fluctuations.

2. **Spatial Patterns**: T distribution was opposite to E but similar to ET, with high T values in northeastern forests and southern croplands, and high E values in sparsely vegetated northwestern areas.
3. **Climate Controls**: VPD and temperature were the dominant factors controlling T and ET across all land cover types. While VPD increases positively contributed to ET, NDVI changes had contrasting effects: increasing NDVI enhanced grassland ET, but decreasing NDVI, particularly in forests, negatively impacted T due to higher sensitivity.

These results improve understanding of water cycle mechanisms in semi-arid ecosystems and provide scientific references for regional water resource management and drought disaster assessment under climate change.

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