Attribution and Response of Water Use Efficiency to Future Changes in the Yellow River Basin

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ABSTRACT

Ecosystem water use efficiency (WUE, defined as the ratio of primary productivity to evapotranspiration, i.e. GPP/ET) has garnered significant attention in recent years for its role as a vital indicator of the interplay between carbon and water cycles. This study delves into the linkage between WUE and the water-energy exchange dynamics within the Yellow River Basin, employing the Budyko framework model as a foundation. We propose and validate a linear Budyko model tailored to WUE, demonstrating satisfactory physical performance. Building on this, we construct an attribution framework for WUE, grounded in the Budyko model and global climate models (GCMs), to quantitatively disentangle the impacts of climate and land use change, as well as to elucidate the mechanisms underlying CO_2-induced radiative and biogeochemical effects on WUE. Our attribution analysis suggests that the WUE of the Yellow River Basin is anticipated to increase by 0.36-0.84 (g C/kg H_2O) in future scenarios, with climate change being the predominant driving force (77.9%-101.4%). Based on the anomaly analysis and the conditional probability model, the response of WUE within YRB to drought exhibited a clear "two-stage" pattern. WUE increased under moderate-severe drought conditions, but as drought intensified, WUE decreased in most regions. Our findings also indicated that with higher carbon emission scenarios, plants' adaptability to water stress improved.

MATERIALS and METHODS

Study area

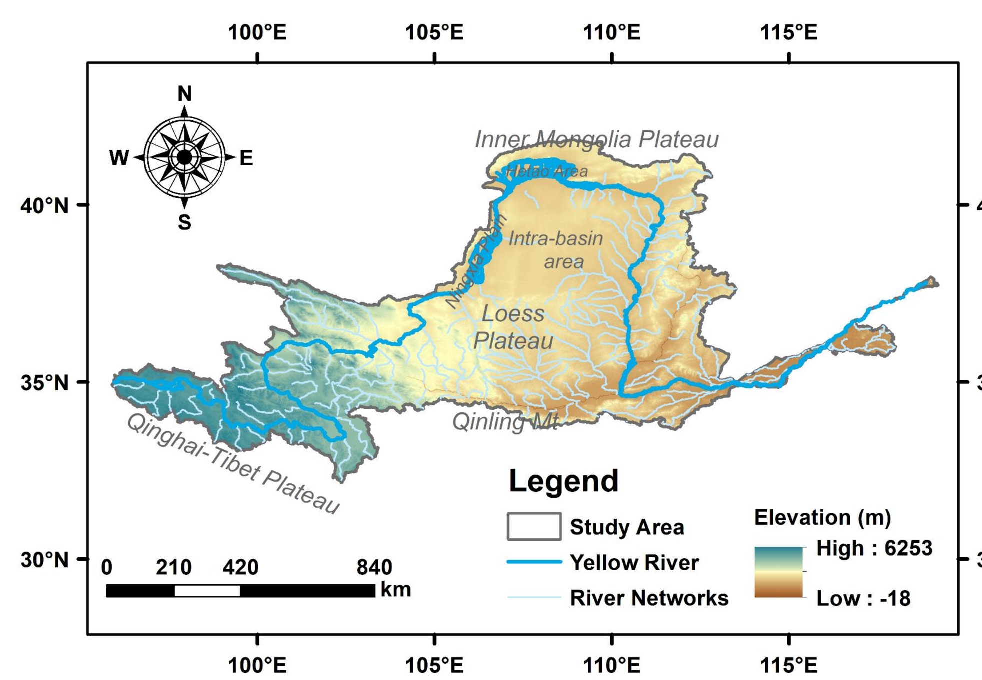

Fig.1 Location of the Yellow River Basin (YRB).

Data

- **Climate and GPP data:**
  National Tibetan Plateau Data Cente
- **Vegetation indicator:**
  GIMMS3g NDVI & GIMMS4g LAI
- **TWSA data:**
  GRACE-REC

Methods

Trend-preserving bias correction

CMIP6 data → Corrected data ← Observation data

Budyko model

$$\frac{WUE}{P} = f\left(\frac{PET}{P}, m, n\right) = m\frac{PET}{P} + n$$

PET: Potential evapotranspiration
m & n: basin underlying surface parameter

Land-atmosphere attribution framework

$$\Delta WUE_c = \alpha\left[\left(\frac{\partial WUE}{\partial P}\right)_1 \Delta P + \left(\frac{\partial WUE}{\partial PET}\right)_1 \Delta PET\right] + (1-\alpha)\left[\left(\frac{\partial WUE}{\partial P}\right)_2 \Delta P + \left(\frac{\partial WUE}{\partial PET}\right)_2 \Delta PET\right]$$

$$\Delta WUE_u = \alpha\left[P_2 \Delta\left(\frac{\partial WUE}{\partial P}\right) + PET_2 \Delta\left(\frac{\partial WUE}{\partial PET}\right)\right] + (1-\alpha)\left[P_1 \Delta\left(\frac{\partial WUE}{\partial P}\right) + PET_1 \Delta\left(\frac{\partial WUE}{\partial PET}\right)\right]$$

Mathematical derivation

ΔWUE_c: changes of WUE due to climate
ΔWUE_u: changes of WUE due to underlying surface

Meta-Gaussian model & Conditional probability

$$Y|X \sim N(\mu_{Y|X}, \Sigma_{Y|X})$$

Y: Standardized WUE Index, SWI
X: TWSA-DSI, a standard drought index
μ, Σ: conditional mean and variance

Analysis

Spatiotemporal distribution | attribution analysis | Response pattern to drought

- **CMIP6 data:**
  Historical, SSP126, SSP245, SSP370, SSP585, CO_2 sensitivity experiment

RESULTS and DISCUSSION

Changes in WUE over YRB

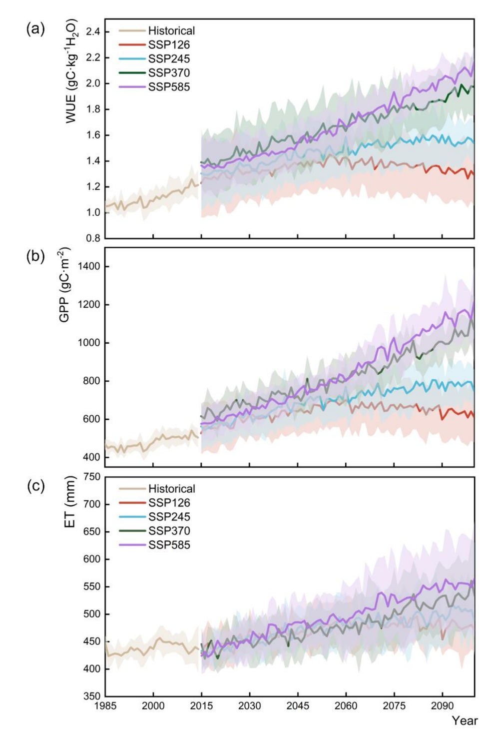

Fig.2 Averaged time series of yearly (a) WUE, (b) GPP, and (c) ET.

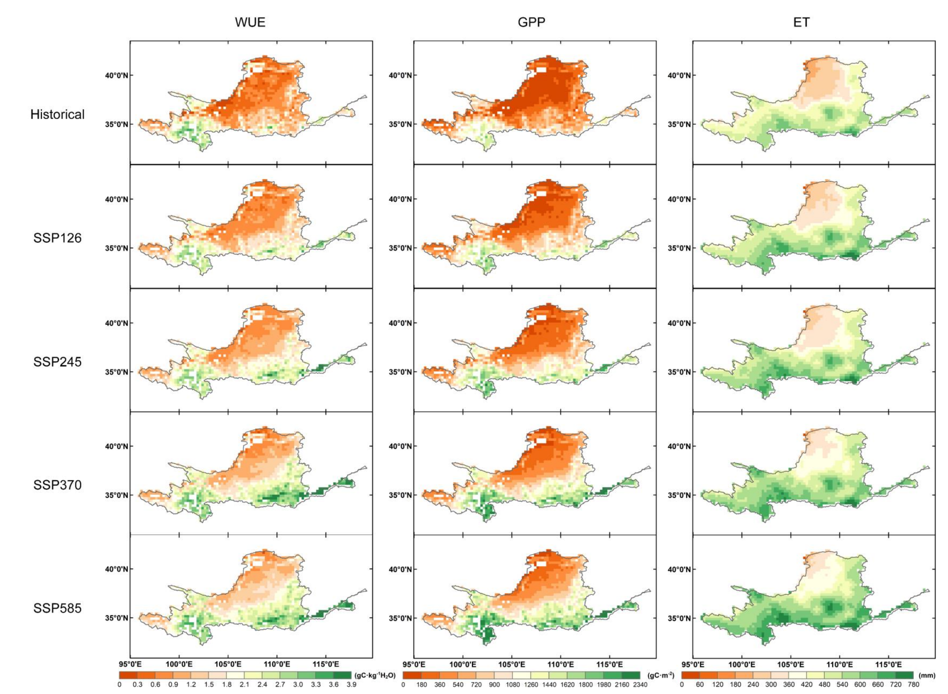

Fig.3 Spatial distribution of multi-model average results under different scenarios.

Fig.2 indicated that during the historical period, WUE and GPP in the YRB showed an increasing trend, while ET exhibited a slight rise with fluctuations. From 2015 to 2100, the changes of each indicator varied in different scenarios, but the trend patterns of WUE and GPP are relatively similar.

Fig.3 showed that the multi-year average WUE and GPP in the YRB predominantly exhibited a pattern of 'higher in the south and lower in the north, higher in the east and lower in the west' both in historical (1985-2014) and future (2070-2099) period. Extremely low values ET were observed in the *Hetao* area, with ET increasing in a radial pattern, indicating higher ET values at locations increasingly distant from this region.

Attribution of WUE changes

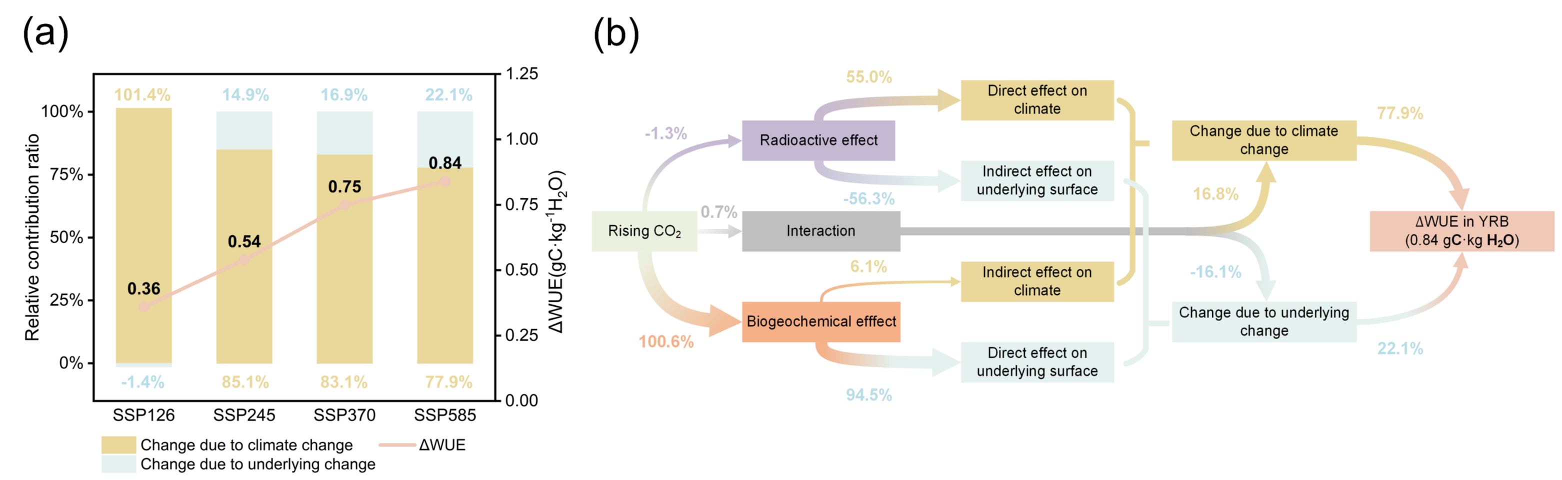

Fig.4 Attribution results for WUE changes

According to **Fig.4 (a),** climate change consistently was the predominant factor influencing WUE changes, especially in SSP126 (101.4%). However, with increasing carbon emissions, the impacts of underlying surface changes on WUE became more important, which could be explained by the fertilization effect of CO_2.

Due to the consistent increase in CO_2 concentration in the three CO_2 sensitivity experiments, with the same rate as in SSP585, we combined the CO_2 experiments with the attribution in SSP585 to decouple the direct and secondary effects of CO_2-induced radiative and biogeochemical impacts in **Fig.4 (b)**.

WUE response to drought

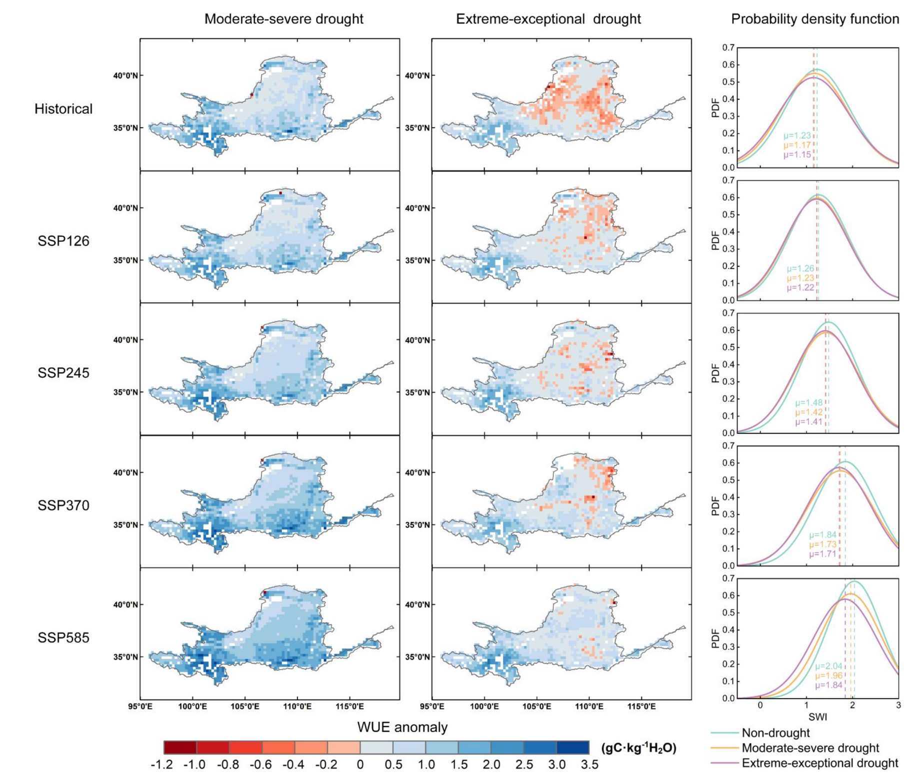

Fig.5 Responses of WUE to different levels of drought.

Fig.5 illustrated that WUE exhibited a **two-stage response pattern** during drought, i.e. it increased under moderate-severe drought but began to decrease as the drought intensifies. This means that under moderate-severe drought condition, plants physiologically adapt to water stress, thereby maintaining a certain level of GPP under limited water conditions. However, as drought intensifies plant physiology is damaged, thereby reducing WUE.

Additionally, with the intensification of carbon emission scenarios (from SSP126 to SSP585), the future response of WUE in the basin to drought becomes more positive, indicating an enhanced adaptability of plants to water stress.

CONCLUSIONS

- In the future, WUE over YRB mainly showed varying degrees of increase under different scenarios. Under SSP126, SSP245, SSP370 and SSP585, the basin averages of ΔWUE are respectively 0.36, 0.54, 0.75 and 0.84 gC·kg-1H_2O respectively
- Compared to underlying surface changes, climate change was the main driving factor for WUE changes, with a relative contribution rate of 77.9-101.4%. However, the relative contribution rate of underlying surface change to WUE increased gradually as the carbon emission scenario intensified.
- In both historical and future periods, the response of WUE in the YRB to drought showed a clear "two-stage" pattern, and the ecosystem's adaptability to drought stress is enhanced in the future as well as under higher carbon emission scenarios.

CONTACT

Access Abstract

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