Variations in Maize Water Use Efficiency Based on Evapotranspiration Partitioning and Its Influencing Factors: Postprint

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Date: 2023-08-25T00:00:00+00:00

Abstract

Water use efficiency (WUE) is an important indicator of carbon-water cycling in agroecosystems and holds significant importance for guiding agricultural irrigation and improving water productivity. The Ningxia Irrigation District is a large-scale irrigation district located in China's arid climate zone, with maize being the crop with the largest planting area. Based on eddy covariance observations of actual evapotranspiration (ET) in agroecosystems, the hydrogen and oxygen stable isotope method was used to partition evapotranspiration into soil evaporation (evaporation, E) and plant transpiration (transpiration, T). Gross primary productivity (GPP) of a typical maize agroecosystem in the Ningxia Yellow River Irrigation District was estimated using a light use efficiency model. Three types of water use efficiency were calculated: canopy water use efficiency WUET=GPP/T, ecosystem water use efficiency WUEET=GPP/ET, and intrinsic water use efficiency IWUEVPD=(GPP · VPD)/ET. Subsequently, the relationships between different water use efficiencies and environmental factors including air temperature, vapor pressure deficit (VPD), CO2 concentration, photosynthetically active radiation, and soil water content were analyzed from three aspects: functional response relationships, correlations, and sensitivities. The results showed that actual evapotranspiration during the growing season of the maize agroecosystem in the Ningxia Yellow River Irrigation District exhibited a single-peak pattern, with crop transpiration showing a consistent trend with actual evapotranspiration. WUET exhibited a "W-shaped" pattern during the growth period, while WUEET and IWUEVPD showed a "single-peak" pattern. The peak values of the three WUE metrics occurred at the tasseling stage, reaching 5.90 kg C · m-3 · H2O, 5.02 kg C · m-3 · H2O, and 32.90 kg C · hPa · m-3 · H2O, respectively. All three water use efficiencies began to decrease during the late grain-filling period. In the late maturity stage of maize, WUET increased slightly due to weak transpiration. WUET, WUEET, and IWUEVPD were significantly positively correlated with soil water content, showing the strongest correlation and sensitivity. VPD was significantly negatively correlated with the three WUE metrics, with the second strongest correlation and sensitivity. Air temperature, photosynthetically active radiation, and CO2 concentration were negatively correlated with the three WUE metrics but were not sensitive factors. Therefore, soil moisture and VPD are the key factors influencing WUE in maize agroecosystems in the Ningxia Yellow River Irrigation District.

Full Text

Changes, Influencing Factors and Sensitivity of Water Use Efficiency in Maize Farmland Ecosystems Based on Evapotranspiration Separation in the Ningxia Irrigated Area

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Abstract: Water use efficiency (WUE) is a critical indicator of the carbon-water cycle in farmland ecosystems and holds significant importance for guiding agricultural irrigation and improving water productivity. The Ningxia Irrigation District represents a large-scale irrigation area located in China's arid climate zone, where maize occupies the largest planting area. Based on eddy covariance observations of actual evapotranspiration (ET) from farmland ecosystems, this study employed the hydrogen and oxygen stable isotope method to partition evapotranspiration into soil evaporation (E) and crop transpiration (T). Using a light use efficiency model, we estimated the gross primary productivity (GPP) of typical maize farmland ecosystems in the Ningxia Yellow River Irrigation Area. We calculated three types of water use efficiency: population-level WUE (WUET = GPP/T), ecosystem-level WUE (WUEET = GPP/ET), and intrinsic WUE (IWUEVPD = GPP $\cdot$ VPD/ET). The relationships between these different WUE metrics and environmental factors—including air temperature, vapor pressure deficit (VPD), CO_2 concentration, photosynthetically active radiation (PAR), and soil water content—were analyzed from three perspectives: functional response relationships, correlation analysis, and sensitivity analysis. Results showed that actual evapotranspiration during the growing season exhibited a single-peaked pattern, with crop transpiration following the same trend. WUET displayed a "W-shaped" variation during the growing season, while WUEET and IWUEVPD showed "single-peaked" patterns. All three WUE metrics peaked at the tasseling stage, reaching 5.90 kg $C \cdot m^{-2} \cdot mm^{-1}$, 5.02 kg $C \cdot m^{-2} \cdot mm^{-1}$, and 32.90 kg $C \cdot hPa \cdot m^{-2} \cdot mm^{-1}$, respectively. In the late maturity stage, WUET increased slightly due to weak transpiration. WUEET and IWUEVPD were significantly positively correlated with soil water content, showing the strongest correlation and sensitivity. All three WUE metrics were significantly negatively correlated with VPD, with the second strongest correlation and sensitivity. Air temperature, PAR, and CO_2 concentration were negatively correlated with the three WUE metrics but were not sensitive factors. Therefore, soil moisture and VPD are the key factors affecting WUE in maize farmland ecosystems in the Ningxia Yellow River Irrigation Area.

Keywords: hydrogen and oxygen stable isotopes; evapotranspiration separation; light use efficiency model; gross primary productivity; crop transpiration

1. Introduction

Water use efficiency represents the amount of carbon fixed per unit mass of water consumed during plant photosynthesis and serves as a key indicator of the carbon-water cycle in farmland ecosystems. Multiple definitions of WUE exist, each offering different perspectives. Typically, WUE is categorized based on research scale into population-level WUE (excluding soil evaporation) and ecosystem-level WUE (including both soil evaporation and plant transpiration as total water consumption). Population-level WUE characterizes the ratio of carbon fixed by plant communities to plant transpiration, while ecosystem-level WUE reflects the dry matter mass fixed by the entire ecosystem per unit mass of water consumed.

Early studies on ecosystem WUE primarily focused on individual and population levels, employing methods such as gas exchange and stable carbon isotope techniques. At the ecosystem scale, WUE determination mainly relied on eddy covariance technology, which has become an advanced method for ET observation and has facilitated breakthroughs in ecosystem-level WUE research. Scholars have demonstrated that vapor pressure deficit significantly influences carbon-water cycles at daily and hourly scales, leading to the introduction of intrinsic water use efficiency, defined as the ratio of GPP multiplied by VPD to evapotranspiration.

Actual evapotranspiration (ET) in farmland ecosystems comprises soil evaporation (E) and crop transpiration (T). Traditional methods for ET separation include sap flow measurements for transpiration and lysimeters for soil evaporation. However, these approaches have limitations: sap flow and lysimeter methods lack spatial representativeness, while model-based separation involves parameter calibration and validation with numerous uncertainties, compromising accuracy. In recent years, hydrogen and oxygen stable isotope technology has emerged as an effective scientific method for studying water consumption structures in terrestrial ecosystems. Its high precision and controllability have enabled widespread application in ET separation, water source tracing, and water cycle research.

Numerous studies have identified PAR, VPD, and soil water content as key environmental factors affecting farmland ecosystem WUE, with nonlinear effects. Therefore, beyond correlation analysis, it is essential to examine the coupled effects of multiple factors on WUE from a holistic perspective. This study partitioned actual ET observed by eddy covariance using hydrogen and oxygen stable isotopes, then investigated WUE variations at population, ecosystem, and intrinsic levels in the Ningxia Yellow River Irrigation Area. We analyzed environmental influences and their global sensitivity to provide scientific guidance for rational irrigation water allocation and improved water productivity.

1.1 Study Area and Experimental Observations

The study area is located in the Yellow River Irrigation Area of Qingtongxia City, Ningxia (Fig. [Figure 1: see original paper]), representing a typical arid and semi-arid region with a temperate continental climate. The area experiences perennial drought with low precipitation, averaging only 189.9 mm annually. The mean annual temperature is 9.2°C, with sunshine percentage exceeding 65% and annual frost-free period of 178 days. Crops include rice, wheat, and maize, with predominant soil types of loam and sandy loam. Groundwater depth exceeds 1.5 m, rising after irrigation or rainfall. Maize was planted with row spacing of 0.6 m and plant spacing of 0.4 m, using border irrigation.

The research was conducted at a long-term farmland ecosystem observation station established by Ningxia University. A 4.5 m eddy covariance tower equipped with a Campbell CPEC310 system and meteorological sensors was installed for continuous observations. The core instruments included a CO_2/H_2O analyzer for flux measurements and a three-dimensional sonic anemometer for wind and temperature data. Auxiliary systems comprised a rain gauge, four-component net radiometer, air temperature/humidity sensors, and wind speed/direction sensors. Soil moisture, temperature, and conductivity sensors (Meter TEROS12) were installed at 0–100 cm depth.

1.2 Sample Collection and Measurement

Sampling was conducted within an 800 m radius of the flux tower, divided into 100 m intervals and 22.5° directional sectors. Three sample types were collected: soil water, maize plant water, and atmospheric water, with sampling conducted once during each growth stage. Based on wind direction and flux contribution, five sampling points were selected equidistantly in each sector, with additional sampling after irrigation.

Soil water samples were collected using an auger at depths of 0–10, 10–20, 20–30, 30–40, 40–60, 60–80, and 80–100 cm, sealed in vials with parafilm and stored in a cooler. Water was extracted using a LI-2000 vacuum condensation system.

Plant water samples were collected from roots and stems of nearby maize plants, sealed and stored similarly.

Atmospheric water samples were collected using a portable multi-channel atmospheric water vapor cold trap (AWVCT04) connected to the flux tower intake line. Condensed water (>2 mL) was sealed and refrigerated.

All samples were analyzed for hydrogen and oxygen stable isotopes using a GLA431-TLW liquid water isotope analyzer, with precision reaching 0.5‰ for δ^{18}O. Meteorological data were recorded by the flux station data logger. NDVI was derived from MicaSense multispectral sensor imagery collected every 7–10 days throughout the growing season.

1.3 Methods

1.3.1 Evapotranspiration Partitioning Based on Stable Isotopes According to isotopic mass balance principles, the isotopic mass of actual ET equals the sum of transpiration and evaporation isotopic masses. A two-source mixing model was applied:

δ^{18}O_{ET} = f_T × δ^{18}O_T + (1 - f_T) × δ^{18}O_E

where δ^{18}O_{ET}, δ^{18}O_T, and δ^{18}O_E represent the oxygen isotope compositions of ET, transpiration, and evaporation, respectively. The fractional contributions of transpiration and evaporation to ET were calculated from these isotopic values.

1.3.2 Gross Primary Productivity Estimation GPP was estimated using the Light Use Efficiency model:

GPP = _{max} × f(Ta) × f(VPD) × APAR

where _{max} is the maximum light use efficiency ($\mathrm{g\ C \cdot MJ^{-1}}$), APAR is absorbed photosynthetically active radiation, and f(Ta) and f(VPD) are correction factors for minimum temperature and vapor pressure deficit, respectively.

APAR was calculated as APAR = PAR × FPAR, where FPAR (fraction of absorbed PAR) was derived from NDVI using a nonlinear semi-empirical model. NDVI was computed from multispectral imagery, with FPAR_{min} = 0.001 and FPAR_{max} = 0.95 determined from cumulative frequency distributions. The parameter α was set to 0.5 for weighting FPAR estimates from NDVI and SR (simple ratio).

Temperature and VPD correction factors followed MOD17 product algorithms:

f(Ta) = (Ta - T_{min})/(T_{opt} - T_{min}) × (T_{max} - Ta)/(T_{max} - T_{opt})[1]

f(VPD) = 1 for VPD $\leq$ VPD_{min}, decreasing linearly to 0 at VPD $\geq$ VPD_{max}.

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[1] (T_{max} - T_{opt})/(T_{opt} - T_{min})

1.3.3 Three Water Use Efficiency Metrics **Population-level WUE (WUET)** characterizes the coupling between carbon fixation and transpiration water consumption, excluding independent soil evaporation:

WUET = GPP/T

Ecosystem-level WUE (WUEET) represents carbon fixed per unit water consumed by the entire ecosystem:

WUEET = GPP/ET

Intrinsic WUE (IWUEVPD) incorporates VPD effects on stomatal regulation:

IWUEVPD = GPP × VPD/ET

1.3.4 Data Analysis Linear regression analyzed trends in environmental factors. The isotopic mass balance model partitioned ET into T and E components. Pearson correlation examined relationships between WUE and environmental factors. Sobol's method assessed sensitivity of WUE to individual and coupled environmental effects.

2. Results

2.1 Environmental Factor Variations

During the growing season, PAR showed a decreasing trend (-0.114 $\mathrm{mol \cdot m^{-2} \cdot d^{-1}}$) with a "dome-shaped" threshold pattern. CO_2 concentration fluctuated between 410–440 ppm for most of the season, increasing to 390–480 ppm after day 190. Air temperature peaked at 31.8°C around day 170, then declined at -0.076°C $\cdot\, \mathrm{d^{-1}}$.

Rainfall occurred primarily from tasseling to filling stages (days 175–240), with maximum daily precipitation of 30 mm. Soil water content (SWC) in the 0–20 cm layer responded sensitively to rainfall (0.221–0.409 $\mathrm{m^3 \cdot m^{-3}}$), while deeper layers (40–100 cm) showed minimal response. Irrigation on day 179 caused SWC increases in all layers, with the magnitude decreasing with depth. During early growth (days 139–170), SWC in 0–20 cm and 20–40 cm layers averaged 0.21 $\mathrm{m^3 \cdot m^{-3}}$, while deeper layers maintained 0.27–0.35 $\mathrm{m^3 \cdot m^{-3}}$.

2.3 Partitioned Evapotranspiration Components

Isotopic partitioning revealed that transpiration dominated ET throughout most of the growing season, with T/ET averaging 0.61 ± 0.01. Both T and ET showed single-peaked patterns, rising from 0.08 $\mathrm{mm \cdot d^{-1}}$ during emergence to 4.20 $\mathrm{mm \cdot d^{-1}}$ at peak. Soil evaporation exceeded transpiration only during early emergence and late maturity when canopy cover was minimal.

Soil evaporation exhibited multi-peaked dynamics: high during emergence, declining as canopy developed, then rising again around day 181 to a first peak.

During grain filling (days 205–239), transpiration weakened while soil evaporation increased again, peaking around day 223 before declining with autumn temperatures.

2.5 Relationships Between WUE and Environmental Factors

Functional response analysis revealed linear negative relationships between air temperature and all three WUE metrics. VPD showed negative power function relationships, with WUE decreasing more rapidly for IWUEVPD than WUEET. CO_2 concentration showed weak negative correlations. PAR exhibited significant linear negative correlations with all WUE metrics. Soil water content showed significant positive linear relationships, with WUE increasing as SWC increased.

Correlation analysis confirmed that WUEET and IWUEVPD were significantly positively correlated with SWC (r = 0.68 and 0.71, respectively). All three WUE metrics were significantly negatively correlated with VPD (r = -0.52 to -0.58). Temperature showed significant negative correlation with IWUEVPD (r = -0.45) but weaker relationships with WUET and WUEET. PAR and CO_2 showed negative but non-significant correlations.

Sensitivity analysis identified SWC as the most influential factor for all WUE metrics, followed by VPD. Temperature, PAR, and CO_2 showed low sensitivity. When considering factor interactions, SWC and VPD remained the dominant drivers, while other factors contributed minimally.

3. Discussion

3.1 WUE Variation Characteristics

The three WUE definitions showed distinct ranges and patterns: WUEET varied from 0.21–5.02 kg $C \cdot m^{-2} \cdot mm^{-1}$, WUET from 4.21–5.90 kg $C \cdot m^{-2} \cdot mm^{-1}$, and IWUEVPD from 5.02–32.90 kg $C \cdot hPa \cdot m^{-2} \cdot mm^{-1}$. Annual mean WUEET (1.11 kg $C \cdot m^{-2} \cdot mm^{-1}$) was lower than WUET (1.77 kg $C \cdot m^{-2} \cdot mm^{-1}$), while both were far lower than IWUEVPD (15.82 kg $C \cdot hPa \cdot m^{-2} \cdot mm^{-1}$). This reflects that soil evaporation, an independent process excluded from carbon-water coupling, reduces ecosystem-level WUE compared to plant-level WUE.

During emergence (days 139–150), low leaf area limited transpiration, resulting in low WUE. From jointing to tasseling, rapid biomass accumulation enhanced transpiration, increasing all WUE metrics. At tasseling (day 199), peak metabolic activity and optimal canopy conditions produced maximum WUE values. During late filling (days 205–239), leaf senescence reduced photosynthesis while soil evaporation increased, causing WUE decline. In late maturity (days 240–259), WUET increased slightly as transpiration decreased faster than photosynthesis, while WUEET and IWUEVPD continued declining.

3.2 WUE-Environment Relationships

Environmental factors, vegetation characteristics, and physiological mechanisms all influence ecosystem WUE. Our results show significant negative correlations between temperature and WUEET/IWUEVPD, consistent with previous studies. In this arid region, elevated temperature increases stomatal conductance, raising transpiration rates more than GPP, thereby reducing WUE. The negative correlation between PAR and all WUE metrics likely reflects photoprotective mechanisms where excessive radiation reduces stomatal conductance to prevent water loss and leaf damage.

VPD emerged as the second most sensitive factor. The significant negative correlation with WUE indicates that high atmospheric water demand suppresses WUE by promoting transpiration while reducing carbon assimilation through stomatal closure. This has important implications for crop yield under high VPD conditions.

Soil water content showed the strongest positive correlation and sensitivity for all WUE metrics, confirming that adequate soil moisture is essential for photosynthesis and dry matter accumulation in this arid irrigation district. The relationship was linear within the observed range, though studies suggest this may plateau under very wet conditions when evaporation losses increase.

CO_2 concentration showed weak correlations and low sensitivity, likely because ambient levels were near optimal for maize photosynthesis, with minimal stomatal response.

3.3 T:ET Ratio and WUE Response

The transpiration to evapotranspiration ratio (T:ET) is a key parameter characterizing ecosystem water use. Our T:ET average of 0.61 aligns with previous studies, though variations occur across ecosystems and climates. The relationship between T:ET and WUE is complex, as WUE depends on both the T:ET ratio and the underlying GPP:T and GPP:ET relationships. In this study, WUE increased with T:ET when transpiration dominated, but the relationship varied by growth stage and environmental conditions.

4. Conclusions

Based on eddy covariance observations and hydrogen-oxygen stable isotope partitioning of evapotranspiration, combined with light use efficiency modeling of GPP, this study investigated three WUE metrics and their environmental sensitivity in the Ningxia Yellow River Irrigation Area. Key findings include:

1. Crop transpiration dominated ET in the maize farmland ecosystem, with similar seasonal patterns to ET. Soil evaporation exceeded transpiration only during early emergence and late maturity.

2. WUET showed a "W-shaped" seasonal pattern, while WUEET and IWUEVPD exhibited single-peaked patterns. All three peaked at tasseling (5.90 kg $C \cdot m^{-2} \cdot mm^{-1}$, 5.02 kg $C \cdot m^{-2} \cdot mm^{-1}$, and 32.90 kg $C \cdot hPa \cdot m^{-2} \cdot mm^{-1}$, respectively). In late maturity, WUET increased while WUEET and IWUEVPD decreased.
3. Among five environmental factors, VPD and soil water content were most critical. All WUE metrics were negatively correlated with VPD and positively correlated with soil water content, with the strongest correlations and sensitivities. Temperature and PAR were negatively correlated but insensitive, while CO_2 showed weak relationships.

In conclusion, the Ningxia irrigation district's maize ecosystems exhibit high transpiration rates. Given the arid climate, optimal VPD and adequate soil moisture are key factors for enhancing WUE. Utilizing crop WUE characteristics across growth stages for rational irrigation management offers a fundamental approach to ensuring agricultural water and food security, providing valuable insights for regional carbon-water cycle research and water resource allocation.

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