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# Evapotranspiration partitioning and energy budget in a rainfed spring maize field on the Loess Plateau, China

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## ABSTRACT

Understanding land–atmosphere interactions in rainfed spring maize fields is important for elucidating land surface processes on the Loess Plateau. In this study, water vapor and energy flux observations were used to investigate the evapotranspiration (ET) partitioning and energy budget in a rainfed spring maize field on the Loess Plateau in 2015 and 2016. Over this 2-year period, the total ET was 851 mm, slightly higher than the total precipitation (847 mm). Plant transpiration (T) accounted for 59% and 56% of ET during the 2015 and 2016 growing seasons, respectively. The most important factor controlling daily ET and soil evaporation was net radiation ($R_n$), and the most important factor controlling daily T was the green leaf area index (GLAI) during the growing season; $R_n$ also controlled ET during the non-growing season. Downward longwave radiation offset 83% of upward longwave radiation in both years; 19% and 18% of downward shortwave radiation was reflected back to the atmosphere by the land surface in 2015 and 2016, respectively. During the growing season, latent heat flux was the largest consumer of $R_n$; during the non-growing season, sensible heat flux was the dominant consumer of $R_n$. Soil heat flux (G) and imbalance energy ($I_{mb}$) did not exhibit obvious seasonal variation pattern, and $G/R_n$ and $I_{mb}/R_n$ values were relatively low during different periods. Midday evaporative fraction (EF), daily crop coefficient ($K_c$), midday Priestley–Taylor coefficient ($\alpha$), and midday surface conductance ($g_s$) increased linearly with increasing GLAI, and the midday Bowen ratio ($\beta$) decreased linearly with increasing GLAI during the growing season. Midday EF, daily $K_c$, and midday $\alpha$ increased exponentially with increasing midday $g_s$, and midday $\beta$ decreased exponentially with increasing midday $g_s$ during the growing season and the non-growing season; the threshold value of midday $g_s$ was approximately 8 mm s$^{-1}$ in the spring maize field.

## 1. Introduction

Water vapor and energy exchange between the land surface and atmosphere is one of the major concerns in the field of ecology (Wang et al., 2010). Evapotranspiration (ET), which corresponds to latent heat flux (LE), is coupled with plant photosynthesis and vegetation productivity in terrestrial ecosystems (Wang et al., 2002; Hao et al., 2007). As an important part of the hydrologic cycle, it drives the biogeochemical cycle (Krishnan et al., 2012). The distribution and redistribution of solar radiation modulate various meteorological variables; determine boundary layer development; and play critical roles in local, regional, and global climatological processes (Wilson and Baldocchi, 2000; Betts, 2001; Chen et al., 2016). Changes in climate and land cover in turn affect energy partitioning on the ground (Baldocchi et al., 2004; Krishnan et al., 2012). Understanding the role of energy exchange processes in the complex feedbacks between land cover and climate is important for predicting ecosystem changes following physical and biological disturbances (Yuan et al., 2014). It is essential to investigate water vapor and energy exchange across different ecosystems to determine the mechanisms that control water and carbon cycles and other ecosystem processes (Hao et al., 2007; Krishnan et al., 2012).

The eddy covariance technique, the sole method that measures turbulent fluxes over an ecosystem in a quasi-continuous long-term manner with minimal disturbance to the ecosystem, has become the standard tool for measuring energy and trace gas exchange between surface and atmosphere in recent decades (Baldocchi, 2008; Chen et al., 2016). Although temporal variation in water vapor and energy fluxes has been studied extensively for tundra, wetlands, forests, grasslands, deserts, and agricultural ecosystems (Wilson et al., 2002; Wu and Wu and Shukla, 2014; Yuan et al., 2014), less attention has been given to semi-arid seasonally water-limited ecosystems (Krishnan et al., 2012). Previous studies on ET and energy exchange in agricultural ecosystems

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have focused mainly on irrigation areas for different crop species (Li et al., 2008, 2009; Suyker and Verma, 2008; Lei and Yang, 2010; Alberto et al., 2014; Yang et al., 2016), whereas rainfed croplands have received limited attention (Suyker and Verma, 2009). In agricultural ecosystems, ET comprises plant transpiration (T) and soil evaporation (E), and E is generally considered as an unproductive form of water use (Kool et al., 2016). Experts must understand how biotic and abiotic variables affect ET and its components to optimize agricultural management and improve the efficiency of crop water use in rainfed croplands. The evaporative fraction (EF) and Bowen ratio (β) are important parameters in energy partitioning on the land surface (Jia et al., 2016; Odongo et al., 2016), the crop coefficient ($K_c$) and Priestley–Taylor coefficient ($\alpha$) are important parameters in eco-hydrological models predicting temporal variation in ET (Ding et al., 2013; Zhao et al., 2015), and the surface conductance ($g_s$) is important parameter for describing the underlying surface development associated with temporal variation in water vapor and energy fluxes (Zhu et al., 2014; Odongo et al., 2016). The temporal variation in these surface parameters should also be determined in semi-arid seasonally water-limited ecosystems.

Arid and semi-arid ecosystems cover approximately 40% of the Earth's land surface and are a significant component of the global climate system (Yuan et al., 2014). The Loess Plateau covers an area of $62.38 \times 10^4\,km^2$, is the largest arid and semi-arid zone in China, and is strongly influenced by the East Asian summer monsoon (Liu et al., 2010; Chen et al., 2016). The land surface processes over this region affect regional climate and atmospheric circulation and monsoon circulation in China (Wang et al., 2010; Chen et al., 2016). As groundwater resources are sparse and deep, most cropland on the Loess Plateau is rainfed, accounting for 40% of the total Chinese rainfed cropland and supporting > 8% of the Chinese population (Zhang et al., 2014; Lin and Liu, 2016). Spring maize (Zea mays L.), the most popular grain crop on the plateau, accounts for 27.3% of the total agricultural area and plays an important role in ensuring regional food security (Liu et al., 2010). The non-growing season in the single spring maize cropping system typically lasts more than half the year; thus, water vapor and energy exchange during this period should have a major effect on the annual water balance and the energy budget on the Loess Plateau. However, few studies using the eddy covariance technique have been conducted on year-round water vapor and energy fluxes in rainfed spring maize croplands on the Loess Plateau.

In this paper, water vapor and energy flux data collected in 2015 and 2016 in a typical rainfed spring maize cropland on the Loess Plateau were used to (1) characterize seasonal variation in ET and its components and identify their important controlling factors; (2) investigate seasonal variation in energy fluxes and determine the energy budget; and (3) assess the effects of crop growth on EF, β, $K_c$, $\alpha$, and $g_s$ and examine the relationships between $g_s$ and other surface parameters.

## 2. Materials and methods

### 2.1. Study site

The data used in this study were collected at the Shouyang Scientific Observing and Experimental Station of the Dryland Agriculture and Ago-environment, Ministry of Agriculture, in the eastern part of the Loess Plateau of Northwest China (37°45′N, 113°12′E, 1202 m a.s.l.). The average annual precipitation is 474.5 mm, concentrated in the East Asian monsoon season from July to September. The average annual air temperature is 8.2 °C, with an average annual frost-free period of 150 days. The soil is sandy–loamy, containing 54.9% sand, 29.5% silt, and 15.6% clay; the soil bulk density is $1.34\,g\,cm^{-3}$.

Spring maize was sown around May 1 at a plant density of approximately $6.67 \times 10^4$ plants $ha^{-1}$ and a plant spacing of 0.3 m. Base fertilization was consistent with the practice of local farmers ($276\,kg\,N\,ha^{-1}$, $144\,kg\,P_2O_5\,ha^{-1}$, and $60\,kg\,K_2O\,ha^{-1}$). Straw is chopped using automated machines and returned to the field at harvest time. Any straw that does not decompose during the non-growing season is completely mixed with the soil through tillage in late April of the following year.

### 2.2. Measurements

The eddy covariance system, including a three-dimensional (3D) sonic anemometer (CSAT3, Campbell Scientific Inc., Logan, UT, USA) and an open-path infrared gas analyzer (LI-7500, Li-COR Inc., Lincoln, NE, USA), was used to measure sensible heat flux (H) and LE at the center of the spring maize field (100 × 260 m). It was kept approximately 1.3 m above the top of the canopy in accordance with the available fetch (ca. 140 m) in the prevailing wind direction. Data were recorded at a frequency of 10 Hz on a data logger (CR5000, Campbell Scientific Inc.).

Air temperature ($T_a$) was recorded at 30-min intervals using a $T_a$ sensor (HMP45C, Vaisala Co., Ltd., Helsinki, Finland). Soil heat flux at 2 cm depth (G) and soil water content at 10 cm depth (SWC) were measured at 30-min intervals using four soil heat flux plates (HFP01SC, Hukseflux B.V., Delft, Netherlands) and a soil moisture sensor (CS616, Campbell Scientific Inc.), respectively. Downward shortwave radiation ($S_d$), upward shortwave radiation ($S_u$), downward longwave radiation ($L_d$), and upward longwave radiation ($L_u$) were collected at 30-min intervals using a net radiometer (CNR4, Kipp & Zonen B.V., Delft, Netherlands). These instruments were also connected to the data logger. A rain gauge (TE525, Texas Electronics Inc., Dallas, TX, USA) connected to a separate data logger (CR3000, Campbell Scientific Inc.) was used to collect precipitation (P) data at 30-min intervals.

During the growing season, seven spring maize plants were randomly selected every 6–10 days for manual measurement of green leaf length and maximum width, and the green leaf area index (GLAI) was calculated according to McKee (1964). Daily E was measured using 10 microlysimeters made from polyvinyl chloride (PVC) tubes with a diameter of 10 cm and a height of 15 cm beginning on the seedling emergence date. The microlysimeters were reinstalled within 1 day after P or on the third day of continuous measurements. Daily E at each microlysimeter was obtained as the difference between the weights measured by an electronic scale with the precision of 0.1 g at sunset, and averaged as daily E in the spring maize field.

### 2.3. Data processing

EddyPro (https://www.licor.com/env/products/eddy_covariance/software.html) was used to process 30-min interval turbulent heat fluxes (LE and H). According to the wind direction and a footprint analysis provided by the software, if > 70% of the 30-min flux footprint overlapped in the area of interest, the data were used for further analysis; otherwise, they were rejected (Wang et al., 2015). Based on the quality control, 11% of all data were rejected in 2015 and 2016. For missing energy fluxes, short gaps (≤ 2 h) were filled using a linear relationship, and long gaps (> 2 h) were filled using the mean diurnal variation (MDV) method described by Falge et al. (2001).

In this study, net shortwave radiation ($S_n$), net longwave radiation ($L_n$), and net radiation ($R_n$) were calculated as follows:

$$S_n = S_d - S_u \tag{1}$$

$$L_n = L_d - L_u \tag{2}$$

$$R_n = S_n + L_n \tag{3}$$

where $S_d$ is downward shortwave radiation, $S_u$ is upward shortwave radiation, $L_d$ is downward longwave radiation, and $L_u$ is upward longwave radiation. Soil evaporation latent heat flux ($LE_e$), plant transpiration latent heat flux ($LE_t$), and evapotranspiration (ET) were calculated as follows: