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Comparison of multi-level water use efficiency between plastic film partially mulched and non-mulched croplands at eastern Loess Plateau of China

Daozhi Gong[a,*], Xurong Mei[a,b,**], Weiping Hao[a], Hanbo Wang[a], Kelly K. Caylor[c]

[a] State Engineering Laboratory of Efficient Water Use of Crops and Disaster Loss Mitigation/MOA Key Laboratory for Dryland Agriculture, Institute of Environment and Sustainable Development in Agriculture, Chinese Academy of Agricultural Sciences, Beijing 100081, PR China
[b] Department of Research Management, Chinese Academy of Agricultural Sciences, 100081, PR China
[c] Department of Civil and Environmental Engineering, Princeton University, Princeton 08544, USA

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ABSTRACT

Multi-level crop water use efficiency, i.e. ratio of productivity to water use at canopy, ecosystem, biomass, grain yield and net biome production (NBP) levels, is essential for evaluating water productivity and footprints of agronomy technologies and may vary with different methods of dryland tillage. This study investigated their changes under two tillage methods: conventional flat tillage without mulching (CK) and plastic film partially mulched furrow-ridge (MFR) for three years through synchronous measurements of two eddy covariance systems with multi micro-lysimeters on the eastern Loess Plateau of China. Water flux linearly correlated to canopy assimilated CO_2 and net ecosystem CO_2 exchange at half-hourly and daily scales, and also to biomass increments at seasonal scale with significant levels for both treatments for all three years. At canopy level, the slopes for these correlations in MFR were very close to those of CK for three years. However, the absolute slopes for these correlations in MFR were always higher than those of CK at ecosystem and biomass levels. Seasonal water use efficiency significantly changed with green leaf area index (GLAI) at ecosystem but not canopy and biomass levels. During three whole growing seasons, average water use efficiency in MFR were higher by 24.4%, 36.7%, 29.3% and 25.7% than those of CK at ecosystem, biomass, grain and net biome production levels, respectively. These results demonstrated that MFR can significantly enhance water use efficiency at ecosystem, biomass, grain and NBP levels except for canopy level, which should help sustainable crop production with minimum water footprints in water-limited environment.

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1. Introduction

To ensure food security in the context of climate change and water crisis in the world, one of the objects for innovating agricultural practices is to make crop produce more with less water, i.e. improve crop water use efficiency (WUE) at different levels. Thus, multi-level WUE has become one of frontiers of agricultural water management (Hsiao et al., 2007; Morison et al., 2008). Recently, partially mulched furrow-ridge tillage (MFR) has been verified by numerous researches as a promising and effective solution to improve WUE in semiarid and arid regions of China (Li et al., 2001; Tian et al., 2003; Yu et al., 2005; Ren et al., 2008; Zhou et al., 2009; Jin et al., 2010; Wang et al., 2011; Liu et al., 2013; Qin et al., 2014). Therefore, it has been widely applied in these regions due to its ability to efficient rainwater collection and soil water conservation, contributing to higher soil water status and grain yield (Gan et al., 2013). This kind of agriculture practice alters water, heat and carbon processes at the interface between soil and atmosphere, which results in increments of abilities to conserve carbon, water and energy, promote crop development, and significantly affects coupling between water and carbon exchange and rainwater use efficiency of the cultivated land in the end. Quantifying the effects of the MFR on multi-level WUE is essential for evaluating its ecohydrological effects and developing efficient rainwater use strategies for China dryland agriculture.

During the past several decades the factors (genotypes and environment) controlling the ratio between CO_2 and vapor exchange fluxes (WUE) and their quantitative relationships with multi-level

* Corresponding author.
** Corresponding author at: Department of Research Management, Chinese Academy of Agricultural Sciences, Beijing 100081, PR China.
E-mail addresses: gongdaozhi@caas.cn (D. Gong), meixurong@caas.cn (X. Mei).

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WUE are always key issues in interdisciplinary fields including agro-hydrology, ecology and crop physiology (Shen et al., 2013; Keenan et al., 2013). Crop genotypes determine WUE at leaf/canopy/stand levels. For instance, canopy WUE for maize (4.1 gC/kgH_2O) is lower than wheat (5.6 gC/kgH_2O) (Tallec et al., 2013). Environmental factors can reverse different genotype WUE at ecosystem level. Shen et al. (2013) reported that WUE of irrigated ecosystem was higher 30% for summer maize than winter wheat in North China due to higher soil evaporation and respiration during drier growing season of the latter. Additionally, soil water availability and atmosphere CO_2 concentration can change ecosystem WUE through adjusting stomotal aperture (Kang and Zhang, 2004; Keenan et al., 2013). Differences of improving WUE by innovative agricultural practices among different levels should be expected due to different key processes of carbon assimilation, respiration associated with water loss and their mainly controlling factors at different levels. Therefore, decrease of soil evaporation and enhancement of soil water availability for crop growth by means of plastic mulching in MFR should result in improvement of ecosystem WUE in the end. However, how much WUE changes with improvements of soil water status in MFR remain unclear at canopy, ecosystem and biomass levels.

Recently, the linkages between ecosystem vapor and CO_2 exchange fluxes have been increasingly paid attentions to address water crisis, energy sustainability, food security and climate change (Suyker and Verma, 2010; Tallec et al., 2013; Tong et al., 2013). Several results showed that there was a significantly linear correlation between ecosystem vapor and CO_2 exchange at different temporal scales. Shurpali et al. (2013), Zhou et al. (2014) and Tong et al. (2009, 2013) found that gross primary productivity (GPP) linearly correlated to evapotranspiration (ET) with significant levels at daily or monthly scales in bio-energy crop and plantations. Monson et al. (2010) also reported that net ecosystem productivity closely linked ET at weekly scale in a high elevation subalpine forest. However, coupling of crop vapor and CO_2 exchanges, and biomass accumulation is not understood in MFR. Elucidating these links will clarify the mechanism that MFR produce more biomass and grain with less water and help to optimize MFR's technique parameters.

Therefore, this study mainly focused on clarifying the linkages between of vapor and CO_2 fluxes and biomass accumulation modified by MFR through eddy covariance and biomass accumulation observations in three growing seasons. Also, we evaluated the effects of MFR on crop WUE at different levels such as canopy WUE (WUE_{can}, GPP/T), ecosystem WUE (WUE_{eco}, NEP/ET), biomass WUE (WUE_b, biomass/total water use), crop WUE (WUE_y, marketable yield/total water use) and biome WUE (WUE_{NBP}, net biome production/total water use).

2. Materials and methods

2.1. Site description and the experimental treatments

The study site was located at Shouyang Experimental Station of Dryland Agriculture and Environment (ESDAE), Ministry of Agriculture, PR China (37°45′58″N, 113°12′9″E) with an elevation of 1202 m. The experiments and data collections were conducted in a rain-fed spring maize field during the three consecutive growth seasons: May 1 through September 28, 2011, May 3 through September 30, 2012 and April 28 through September 25, 2013. The soil type is a cinnamon soil with light clay loam texture. At the effective root depth (0–100 cm), the average volumetric soil water concentration at field capacity and the average bulk density were 0.36 $m^3\ m^{-3}$ and 1.34 g cm^{-3}, respectively. Groundwater existed at more than 150 m depth below ground surface. The climate type at this site is a typical continental temperate with an average daily temperature of 7.4 °C, an average annual rainfall of 481 mm and an average number of frost-free days 140d. 80% of annual rainfall often concentrates the growing season of spring maize and is generally associated with prominent southwest wind.

In this study, we designed two treatments during the maize growing seasons of 2011 through 2013: planting in flat field without mulching (CK) and plastic film mulched furrow-ridge (MFR). In CK treatment, maize was sowed in north-south rows with a distance between ones equal to 50 cm and a space within rows of 30 cm. As to MFR treatment, maize was sowed in both sides of each plastic film mulched ridge with a space within rows of 30 cm. The widths of ridges and furrows were about 60 cm and 40 cm, respectively, and the height of ridge was about 8–12 cm. Only the ridge was covered by plastic film in MFR. The area of each experiment plots was about 3.0 ha of which length and width was 200 m and 150 m, respectively, which meeted the minimum fetch requirement of eddy covariance system installation.

2.2. Measurements of water vapor and carbon dioxide fluxes and their components

In the central of each plot, water vapor and carbon dioxide fluxes between atmosphere and canopy were measured by an open-path eddy covariance technique. The eddy covariance system (LI-COR, Inc., Lincoln, NE, USA) were composed of a three-dimensional supersonic anemometer (CSAT-3) and a CO_2/H_2O infrared gas analyzer (Li-7500). The height of sensors installment was often adjusted to keep the relative height between sensors and maize canopy constant (0.5 m). Specific time length depended on the increments of canopy height. The observation site had a wide fetch of at least 75 m in all directions, which allowed us to neglect heat advection in the maize field. Before the experiment, two sets of sensors and analyzers were calibrated to acquire data at the same standard and decreases the error depend on different instruments. Calibration of the two sets of gas analyzers was performed using chemical absorption columns for zero values and a compressed gas source of CO_2 at 600 ± 10 mmol/mol (Linde, Linde Gas Group, England) and a portable dew point generator (Li-610, LI-COR, Inc., Lincoln, NE, USA).

For verification of energy balance and flux corrections, short-wave and long-wave radiation from the sky and the land surface was measured at 3.5 m above ground by a four-way net radiometer (CNR1, Kipp&Zonen Inc., Delftechpark, The Netherlands). Soil surface temperatures (0.02 m and 0.06 m below soil surface) and soil heat flux were measured with temperature probes (TCAV, Campbell Scientific Inc., USA) and self-calibrating heat flux sensors (HFP01, Campbell Scientific Inc., USA) buried 0.02 m below the soil surface at three different points. The averaged data were used in our analysis. Based on energy balance principle, the accuracy of the EC system measurements were evaluated.

Fluctuations in wind speed, sonic virtual temperature, CO_2 and H_2O concentrations were sampled with the digital micro-logger at 10 Hz. Flux values were recorded in 30 min intervals with a data-logger (CR5000, Campbell Scientific Inc., USA). Barford et al. (2003) and Verma et al. (2005) suggested that while U less than 2.5 m/s, CO_2 and H_2O flux data were deleted to reduce errors related to insufficient turbulent mixing at night. WPL density corrections were applied to fluxes of H_2O and CO_2 (Webb et al., 1980). Linear interpolations between values adjacent to missing or abnormal value(s) was used for filling small (less than two hours) gaps, but mean diurnal variation (MDV) of previous or afterwards periods was used for greater gaps above two hours (Falge et al., 2001).

Micro-lysimeter was adopted in this study to estimate soil evaporation on the rainless days (Boast and Robertson, 1982). Considering partially plastic mulching and uneven coverage of the maize foliage, which gives rise to the heterogeneity in the com-

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