Agricultural Water Management 209 (2018) 142–150

Contents lists available at ScienceDirect

Agricultural Water Management

journal homepage: www.elsevier.com/locate/agwat

Differences in ecosystem water-use efficiency among the typical croplands

Tongxin Wang[a], Xuguang Tang[a,b,c,*], Chen Zheng[a], Qing Gu[a], Jin Wei[a], Mingguo Ma[a,c]

[a] Chongqing Engineering Research Center for Remote Sensing Big Data Application, School of Geographical Sciences, Southwest University, Chongqing 400715, China
[b] Institute of Geographic Sciences and Natural Resources Research, Chinese Academy of Sciences, Beijing 100101, China
[c] Research Base of Karst Eco-environments at Nanchuan in Chongqing, Ministry of Nature Resources, School of Geographical Sciences, Southwest University, Chongqing 400715, China

ARTICLE INFO

Keywords:
Water-use efficiency
Cropland
GPP
ET
C_3/C_4 plant

ABSTRACT

Water use efficiency (WUE) is an important parameter to assess agricultural production and the reasonable utilization of water resources. Especially in the context of changing hydrological environment, more attention need to be paid on how to use limited water resource to improve crop yield for ensuring food security. Based on 33 site-years of flux measurements over 10 cropland sites using the eddy covariance (EC) technique, the study systematically evaluated the large differences in seasonal and interannual variations of gross primary productivity (GPP), evapotranspiration (ET) and ecosystem WUE across the four crops worldwide including soybean, maize, winter wheat and paddy rice. The lengths of the growing seasons across the main crops extracted from time-series MODIS NDVI data, implied that the longest growth period in winter wheat and the shortest growing season in paddy rice field. Further analyses suggest that maize cropland has the strongest ecosystem WUE with 2.48 ± 0.69 g C kg^{-1} H_2O, followed by winter wheat (2.00 ± 0.39 g C kg^{-1} H_2O), soybean (1.92 ± 0.52 g C kg^{-1} H_2O), and paddy rice (1.88 ± 0.63 g C kg^{-1} H_2O). Meanwhile, the variability in ecosystem WUE exhibited apparent seasonality, and peaked together with GPP in the most active summertime. A series of biotic and abiotic factors affected the GPP as well as WUE variability. Given the complicated interactions among these environmental factors, this study revealed the great potential to remotely retrieve the WUE variability using time-series MODIS NDVI data over large areas. Ecosystem WUE of the C_4 crop –maize was obviously higher than the other three C_3 crops. Engineering C_4 feature into C_3 crops may be a feasible way to increase photosynthesis and yield.

1. Introduction

Global mean temperature has increased substantially due to the increasing of atmospheric CO_2 concentration (Solomon et al., 2009). Croplands, as one of the most important terrestrial ecosystems, are facing serious threats with the global climate change. According to statistics, world grain reserves are fast declining, and crop areas have continuously reduced due to various environmental problems and urbanization (Molden, 2007; Jiang, 2009; Liu et al., 2016). Meanwhile, world population is gradually increasing, competition for water resources among urban area, agricultural activities and nature is sharp (Flavin and Gardner, 2006), which makes agricultural water management for food security more strict. Recently, how to make good use of scarce water resources and improve the water-use efficiency of agriculture has become the focus issue of grain production (Dietzel et al., 2016). Frequent food crisis like food shortage and unsafe food are becoming the new challenges of human being, which will get worse unless agricultural scientists find proper solutions (Hanjra et al., 2009).

Water use efficiency (WUE) reflects the ability of the crop to produce biomass per unit of water consumption through evapotranspiration (Sadras and Rodriguez, 2007). With the development of eddy covariance (EC) technique, it has become a direct and efficient micrometeorological flux measurement method of carbon, water and energy at ecosystem scale (Law et al., 2002; Loescher et al., 2006; Beer et al., 2009; Liu et al., 2015). Then, ecosystem WUE is often characterized by the amount of CO_2 fixed by photosynthesis per unit of water loss through evapotranspiration (ET) including plant transpiration and soil evaporation (Tang et al., 2014). The EC system can also be used to assess the potential impacts of abnormal temperature, drought and flood events on GPP, ET as well as ecosystem WUE (Reichstein et al., 2007; Baldocchi, 2008). Currently, the AmericaFlux, EuroFlux, AsiaFlux and other regional research networks jointly form the global

* Corresponding author at: Chongqing Engineering Research Center for Remote Sensing Big Data Application, School of Geographical Sciences, Southwest University, Chongqing 400715, China.
E-mail address: xgtang@swu.edu.cn (X. Tang).

https://doi.org/10.1016/j.agwat.2018.07.030
Received 26 May 2018; Received in revised form 25 July 2018; Accepted 25 July 2018

Table 1
Descriptions of the flux tower sites of croplands used in this study.

Crop type	Site ID	Latitude (°)	Longitude (°)	MAP (mm)	MAT (°C)	Available year	References
Soybean	US-Bo1	40.0062	−88.2904	991	11.00	2002/2004/2006	Meyers et al., 2012
	US-Ro1	44.7143	−93.0898	806	10.10	2008/2010/2012	Griffis et al. (2008)
	US-IB1	41.8593	−88.2227	1009	9.27	2007/2009/2011	Allison et al. (2005)
Maize	US-Bo1	40.0062	−88.2904	991	11.00	2003/2005/2007	Meyers and Hollinger, 2004
	US-Ro1	44.7143	−93.0898	806	10.10	2007/2009/2011	Griffis et al. (2008)
	CN-Daman	38.8556	100.3722	126.7	7.20	2013–2015	Song et al. (2016)
Winter wheat	BE-Lon	50.5516	4.7461	800	10.00	2006/2007, 2008/2009	Aubinet et al. (2009)
	DE-Seh	50.8706	6.4497	698	9.90	2007/2008, 2008/2009	Schmidt et al. (2012)
	US-ARM	36.6058	−97.4888	843	14.76	2006/2007, 2009/2010	Lu et al. (2017)
Paddy rice	IT-Cas	45.0628	8.6685	576.4	13.20	2008–2010	Skiba et al. (2009)
	US-Twt	38.1087	−121.6530	421	15.60	2011–2013	Xin et al. (2017)
	JPN-MSE	36.0540	140.0269	1200	13.70	2003–2005	Xin et al. (2017)

Note: MAP and MAT represent multi-year mean precipitation and temperature, respectively.

carbon flux observation network (FLUXNET). It provides data support for analyzing the characteristics of carbon and water cycles in different ecosystems, and is conducive to regional, national and global evaluation (Saigusa et al., 2013). At the regional scale, the estimation of ecosystem WUE mainly uses the ecological model incorporating remote sensing data to calculate the ratio of GPP to ET. At present, models for calculating vegetation GPP mainly include light use efficiency model, such as CASA (Potter et al., 2003), VPM (Xiao et al., 2004), EC-LUE (Yuan et al., 2014), etc. The ET estimation model based on remote sensing data has also been developed rapidly in recent years, such as the surface energy balance model generated by Penman-Monteith equation (Cleugh et al., 2007). The equation has the advantages of simple and strong mechanism to be successfully applied to various land surface covers and climate conditions, and the MODIS ET product is produced on the basis of it.

As an important component of adaptation to water stress, WUE is crucial to the development of precision agriculture to realize water-saving irrigation (Tang et al., 2015). Particularly, it is significant for the sustainable development of agriculture in arid and semi-arid areas which are under the condition of severe water shortage (Bu et al., 2013; Kühling et al., 2018). The current applications of various water-saving technologies and management measures are ultimately aimed to improve the WUE of croplands (Katerji et al., 2008). Generally, it is carried out from three angles in practice: irrigation water use rate, rainfall water use rate and crop water use efficiency. Plenty of researches focused on the effects of irrigation engineering and technology, and the utilization rate of precipitation in water-deficient areas (Wallace, 2000; Evans and Sadler, 2008; Roth et al., 2013; Gu et al., 2018), but there lack of systematic and in-depth study on WUE which takes the different crops as the core. Affected by different understanding from different disciplines, WUE of crops has experienced three levels from leaf level to group level and yield level (Blum, 2005; Niu et al., 2011). The WUE at the leaf level is the amount of organic matter formed by per unit of water loss through transpiration. In group level, WUE is the ratio of CO_2 flux to crop evapotranspiration, which is closer to the reality than the single leaf level. At the yield level, WUE refers to how much water consumed during the accumulation of dry matter. The water consumption not only includes the transpiration of crops, but also the evaporation from the soil surface, which is more practical for the research of water-saving agriculture (McCarthy et al., 2011; Tang et al., 2017).

The carbon and water cycles of cropland ecosystems are reciprocal feedback on different spatiotemporal scales. As an important indicator to characterize the coupling relationship of carbon and water fluxes, the seasonal and interannual patterns of crop WUE and its environmental controls are being paid close attentions by current global change ecology researches, which is important for future food security especially in the face of frequent climate anomalies (Baldocchi, 2008; Gornall et al., 2010; Yu et al., 2018).

Croplands cover ~15 million km^2 of the planet and provide the bulk of the food and fiber essential to human well-being (Monfreda et al., 2008). Maize, wheat, rice and soybean are the most widely produced grain for humans and livestock around the world. Therefore, quantitative assessment of the temporal patterns and environmental control of ecosystem WUE over the main crops will help to project the influence of future climate change on the carbon and water cycling processes of the cropland, and to realize the key to water-saving irrigation. In this study, we aimed: 1) to reveal the differences in seasonal and interannual dynamics of ecosystem WUE across four typical crops worldwide including soybean, maize, winter wheat and paddy rice based on 10 EC-based flux sites; and 2) to explore the underlying environmental controlling mechanisms in the WUE variability of different crop types by means of the relevant meteorological data, biophysical parameter and photosynthetic pathway. All analyses are of great theoretical and practical significance to provide scientific supports for agricultural water management at the regional and national scale.

2. Methods and materials

2.1. Descriptions of the flux sites

In total of 33 site-years flux data over four typical croplands in North America, Europe and Asia were used for analysis in the study (Table 1). Three maize flux sites included US-Bo1, US-Ro1 and CN-Daman. The US-Bo1 site is located in Illinois, the United States with the climate of temperate continental. The flux tower has been operated since 1996. The crops cultivated in this land are maize and soybean rotation (maize in the odd years and soybean in the even years). (Bernacchi et al., 2005; Meyers and Hollinger, 2004; Tang et al., 2015). The US-Ro1 site lies in the University of Minnesota's Rosemount Research and Outreach Center. This area has similar climate type as US-Bo1. Maize and soybean are also planted in this site with maize in the odd years and soybean in the even years. (Griffis et al., 2008; Kalfas et al., 2011; Tang et al., 2015). The CN-Daman site is located in the middle of Heihe River basin of Northwest China. The flux tower has been operated since 2012. (Liu et al., 2011; Song et al., 2015, 2016).

Three soybean flux sites were comprised of US-Bo1, US-Ro1 and US-IB1. Detailed introduction of US-Bo1 and US-Ro1 has been described. The US-IB1 site lies in Fermi National Accelerator Laboratory in the United States. The field has been rotated between maize and soybean since 1992, with maize in the even years and soybean in the odd years (Allison et al., 2005).

The study used three flux sites of winter wheat. The BE-Lon site is in Lonzée, Belgium and started to work in 2004. This area has temperate maritime climate. The rotation crop are sugar beet, winter wheat, seed potato and winter wheat again (Rannik et al., 2003; Aubinet et al.,