Agricultural Water Management 148 (2015) 24–33

Contents lists available at ScienceDirect

Agricultural Water Management

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

Ecosystem water use efficiency for a sparse vineyard in arid northwest China

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ARTICLE INFO

Article history:
Received 29 August 2013
Received in revised form 9 August 2014
Accepted 12 August 2014
Available online 28 September 2014

Keywords:
Carbon dioxide flux
Evapotranspiration
Sparse vegetation
Vineyard
Water use efficiency

ABSTRACT

Ecosystem water use efficiency (*WUE*) can be defined as the ratio of net CO_2 exchange to evapotranspiration, which implicates the interactions between carbon sequestration and water consumption. Previous studies mainly focused on ecosystem *WUE* for forests, grasslands and farmlands, but paid little attention to the sparse vineyard. How the vineyard *WUE* varied on daily and seasonal time scales remains uncertain. The vineyard CO_2 and water fluxes were measured by the eddy covariance method during 2008 in arid northwest China to address the issues. Results indicate that the seasonal variation of vineyard *WUE* presented a downward-parabolic trend, with a mean value of 4 mg g^{-1} and a maximum value of 10 mg g^{-1}. Compared with other ecosystems, *WUE* for vineyard was lower than that for forests, maize, wheat and wetlands, but higher than grasslands and Savannas. The severely dry climate and the sparse vegetation led the results. Such factors as radiation, air temperature and humidity, soil moisture, canopy conductance and leaf area index all exerted significant influences on vineyard *WUE*. However, the vineyard *WUE* was highly sensitive to solar radiation and air temperature changes, and it decreased significantly with the rising radiation and temperature, which is remarkably different from previous studies. Such results were mainly due to the great impact on CO_2 exchange exerted by soil layer in the sparse vineyard, and the high sensitivity of soil respiration to temperature changes induced by radiation and air temperature. The CO_2 assimilation reduced with the increasing radiation and air temperature, however the vineyard evapotranspiration increased rapidly, thus the vineyard *WUE* declined significantly with the rising radiation and air temperature. These results provided a new insight for understanding the carbon and water cycles over the sparse vegetation.

1. Introduction

Ecosystem water use efficiency (*WUE*, mg g^{-1}) can be defined as the ratio of net ecosystem productivity (*NEP*, mg CO_2 m^{-2} s^{-1}) to evapotranspiration (*ET*, g H_2O m^{-2} s^{-1}) (Baldocchi, 1994; Scanlon and Albertson, 2004; Kuglitsch et al., 2008). It connects the ecological processes and hydrological processes and implicates the interaction between carbon sequestration and water consumption. Currently, global climatic changes such as the rise in CO_2 concentration and the global warming have significantly altered ecosystem *WUE* through influencing photosynthesis and transpiration (Tao et al., 2008; Guo et al., 2010; Allen et al., 2011; Keenan et al., 2013). Thus exploring the ecosystem *WUE* is critical in revealing the response of ecological and hydrological processes to global climatic changes and optimizing the water and carbon managements in practice (Brouder and Volenec, 2008; Green et al., 2010; Grewal et al., 2011; Keenan et al., 2013; Liu and Tao, 2013).

Ecosystem *WUE* is mainly controlled by such environmental factors as soil moisture, atmospheric CO_2 concentration, air temperature and humidity and solar radiation and also by physiological factors such as canopy conductance and leaf area index. Its regulation and controlling mechanism is similar to that at leaf scale, but different in the aspect that ecosystem *WUE* involves in and is influenced by both vegetation and soil. It is the combined effects of processes like photosynthesis, respiration, evaporation and transpiration. Thus ecosystem *WUE* has a far more complicated controlling mechanism than that at leaf scale.

So far, scientists have conducted many researches on ecosystem *WUE*. Baldocchi (1994) indicated that the maximum *WUE* for maize and wheat in the growing season could reach 15 mg CO_2 g^{-1} H_2O.

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http://dx.doi.org/10.1016/j.agwat.2014.08.011
0378-3774/

Law et al. (2002) showed that the ratio of carbon gain to water loss was 3.4 mg g^{-1} for grasslands, 3.2 mg g^{-1} for deciduous broadleaf forests, 3.1 mg g^{-1} for crops, 2.4 mg g^{-1} for evergreen conifers and 1.5 mg g^{-1} for tundra vegetation. Ponton et al. (2006) indicated that the average *WUE* for grassland, aspen and Douglas-fir was 2.6, 5.4 and 8.1 mg g^{-1}, respectively. Zhao et al. (2007) indicated that the *WUE* of wheat in north China Plain reached a peak value of 14 mg g^{-1}. Clement et al. (2012) indicated that the forest in Scotland sequestered about 6 tonnes of C per hectare per annum using the 5 years of eddy covariance measurements. In a latest paper published in Nature, Keenan et al. (2013) found a substantial increase in water-use efficiency in temperate and boreal forests of the Northern Hemisphere over the past two decades, and indicated that the increase is most consistent with the strong CO_2 fertilization effect.

Vineyards are usually planted in the form of the single vertical trellis and wide row so as to ensure sufficient illumination and favorable ventilation. In this sense, the vineyard can be considered a sparse ecosystem. Many studies have indicated that soil evaporation could account for 50% of total *ET* over the entire growth stage (Zhang et al., 2008). By virtue of the notable difference in water and carbon transports between the soil layer and the vegetable layer in the vineyard, the sparse ecosystem like the vineyard needs substantial study on relationships between *WUE* and environmental and physiological factors and how such factors regulate *WUE*.

To address these questions, the eddy covariance method is adopted in the vineyard in arid northwest China to measure water and carbon fluxes during the whole growth period, with the aim to: (1) analyze the daily and seasonal variations of ecosystem *WUE* for the sparse vineyard and its difference from the *WUE* for other ecosystems and (2) reveal the response patterns of vineyard *WUE* to environmental and physiological factors such as radiation, air temperature and humidity, CO_2 concentration, soil moisture, canopy conductance and leaf area index.

2. Materials and methods

2.1. Experimental site and description

The experiment was conducted at Shiyanghe Experimental Station for Water-saving in Agriculture and Ecology of China Agricultural University, located in Wuwei City, Gansu Province of northwest China (N37°52′, E102°50′, altitude 1581 m) during May 1st to September 25th, 2008. The experimental site is located in a typical arid zone where mean annual temperature is 8 °C, annual accumulated temperature (>0 °C) 3550 °C, annual precipitation 164 mm, mean annual pan evaporation approximate 2000 mm, the average annual duration of sunshine 3000 h and the average number of frost free days 150 days. The groundwater table is 40–50 m below the ground surface (Li et al., 2008, 2012, 2013a,b)

Measurements in the vineyard were made in a field with a length of 1650 m and a width of 1400 m in 2008. The area was planted with grapevines (*Vitis vinifera L.* cv Merlot Noir) in 1999 with row spacing of 270 cm and plant spacing of 100 cm. The trellis for grapevine was 1.5 m in height. The soil texture is sandy loam, with a mean dry bulk density of 1.47 g cm^{-3}, porosity of 52%, field capacity of 0.35 cm^3 cm^{-3} and a permanent wilting point of 0.12 cm^3 cm^{-3} for the 0–100 cm layers. Furrow irrigation was conducted five times on 18th May, 24th June, 18th July, 16th August and 9th September with total 420 mm in the vineyard. The precipitation was 79 mm during May 1st–September 25th, 2008.

2.2. Eddy covariance measurement and correction

An opened eddy covariance system (Campbell Scientific Inc., USA) was installed at 4.2 m above the ground at the northwest of vineyard according to the prevailing wind direction. The least fetch exceeded 600 m, which can fully meet the requirements of *EC* measurement. Measurements were made continuously from May 1st to October 11th in 2008. Net radiation (R_n) was measured by a net radiometer (model NR-LITE, Kipp & Zonen, Delft, Netherlands) at a height of 4.5 m above the ground. Four soil heat flux plates (model HFP01, Hukseflux, Netherlands) were used to measure soil heat flux.

The procedures conducted for correcting the eddy covariance measurements included: (1) 10-min interval for eddy flux computation (Twine et al., 2000); (2) the signal asynchrony correction (Wolf et al., 2008); (3) the oxygen-correction proposed by Tanner and Greene (1989); (4) planar fit method for coordinate rotation (Finnigan et al., 2003; Paw et al., 2000); (5) density correction according to the method of Webb et al. (1980) and (6) filling data gaps using the mean diurnal variation (*MDV*) method (Falge et al., 2001).

In this study, sum of vineyard ($\lambda ET + H$, w m^{-2}) accounted for 95% of available energy ($R_n - G$, w m^{-2}) over whole experimental period. For the daytime *EC* data, the measured energy budget components were forced to close using "Bowen-ratio closure" method proposed by Twine et al. (2000), which assumes that Bowen-ratio is correctly measured by the *EC* system. But for the nighttime *EC* data, especially when the available energy was below zero, another method – the "residual λET closure" method also proposed by Twine et al. (2000) was adopted to close the energy balance in our study. This method assumed that the *EC*-based *H* was accurately measured, and solved for λET as the residual to the energy-balance equation. After forcing the energy balance to be closed, the λET data by the *EC* system (λET_{EC}) were adopted in the following analysis (Li et al., 2013a,b).

2.3. Other measurements

Soil moisture content was measured using portable device (Diviner 2000, Sentek Pty Ltd., Australia) (Li et al., 2013a,b). Fifteen PVC access tubes with the depth of 1.2 m were evenly inserted in the soil in the ditch, shaded and non shaded parts of the ridge, respectively. The measurements were calibrated by the oven drying method. The normalized soil water content of 0–1 m layer is calculated as: $F(\theta) = (\theta - \theta_w)/(\theta_f - \theta_w)$, where θ is the measured soil water content, θ_f is the field capacity, θ_w is the wilting coefficient. Leaf area index was measured every 10 days using AM300 portable leaf area meter (ADC BioScientific Ltd., UK), respectively.

2.4. Calculation of canopy conductance using the re-arranged Penman-Monteith equation

The Penman–Monteith (PM) model can be written as (Monteith, 1965):(1)$\lambda \mathrm{ET} = \frac{\Delta(R_n - G) + C_p \rho_a \mathrm{VPD}/r_a}{\Delta + \gamma + \gamma(r_s/r_a)}$

where λ is the latent heat of vaporization (J kg^{-1}), *ET* the crop evapotranspiration, Δ the slope of the saturation water vapor pressure versus temperature curve (kPa K^{-1}), R_n the net radiation (W m^{-2}), *G* the soil heat flux (W m^{-2}), C_p *the* specific heat of dry air at constant pressure (J kg^{-1} K^{-1}), ρ_a the air density (kg m^{-3}), VPD *the* water vapor pressure deficit (kPa), r_a the aerodynamic resistance (s m^{-1}), γ the psychrometric constant (kPa K^{-1}) and r_s the canopy resistance (s m^{-1}). The aerodynamic resistance r_a can be calculated as (Thom, 1972):(2)$r_a = \frac{\ln((z-d)/(h_c-d))\ln((z-d)/z_0)}{k^2 u}$

where *z* is the reference height (m), *d* the zero plane displacement (m), h_c the mean crop height (m), z_0 *the* roughness length of the crop relative to momentum transfer (m), *k* the von Karman constant (0.40) and *u* (m s^{-1}) the wind speed at the reference height measured by eddy covariance. According to Monteith (1965), *d* can be calculated as 0.67 h_c, z_0 as 0.13 h_c.