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Measurements of water dissipation and water use efficiency at the canopy level in a peach orchard☆

Z.-P. Ouyang[a], X.-R. Mei[b], Y.-Z. Li[b,*], J.-X. Guo[a,*]

[a] Beijing Key Laboratory of New Technology in Agricultural Application, College of Plant Science and Technology, Beijing University of Agriculture, No. 7 Beinong Road, Changping District, Beijing 102206, PR China
[b] Water Resources and Dryland Farming Laboratory, Institute of Agricultural Environment and Sustainable Development, Chinese Academy of Agricultural Sciences, No. 12 Zhongguancun South Street, Haidian District, Beijing 100081, PR China

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ABSTRACT

Water deficit is the main limiting factor for agricultural production in the dry regions of northern China. Previous studies on water–plant relationships in fruit trees have focused mainly on ecological, physiological and molecular responses to water stress at the leaf or tree-scale; few equivalent studies have been conducted at the ecosystem-scale. In this study, we monitored water vapour exchange and water use efficiency (WUE) in a no-till, 12-year-old peach orchard using an eddy covariance technique. Daily average values of actual evapotranspiration (ET_a) and WUE were 2.3 ± 2.1 mm and 0.44 g CO_2 kg^{-1} H_2O, respectively, across the monitoring period. Daily changes in WUE at the canopy level were strongly influenced by atmospheric vapour pressure deficit (VPD) during stages rapid plant growth. The rank order of WUE across developmental stages was: fruit post-harvest stage > fruit de-greening and red-colouring stage > flowering period and early fruit enlargement stage. The trends of water dissipation and WUE both had single peaks. During the late period of fruit enlargement, the rate of actual evapotranspiration was very high, reaching a daily maximum value of 7.1 mm d^{-1}. Average daily WUE ranged up to 2.1 g CO_2 kg^{-1} H_2O, peaking after fruit harvest. The annual cumulative actual evapotranspiration reached 790.6 mm, with a crop coefficient 1.08. In conclusion, WUE was strongly influenced by VPD in the daytime during peach development, and the key stage of water requirement occurred in the period following the onset of fruit ripening in the orchard.

1. Introduction

About 1 million ha of land in China is currently under peach tree cultivation. Most of the orchards are in northern China where the climate is arid or semi-arid and water for human use is scarce. Land suitable for crop production is limited and peach orchards have been planted in terrain that is either hilly or otherwise unsuitable for crop cultivation. Hence, the peach trees frequently suffer serious drought stress. Measures of plant evapotranspiration and water use efficiency (WUE) are important indicators of the responses of plants growing under different soil water conditions, including drought (Wang, 1991). In the past, these two parameters have been determined at the scale of leaves or whole trees, in studies of physiological and molecular mechanism responses to environmental factors (Cheng and Luo, 1990; Williams et al., 2004; Dong et al., 2005; Gao et al., 2006; Abrisqueta et al., 2012), and as components of irrigation management measures (De Azevedo et al., 2006; Cheng et al., 2007; Qassim et al., 2013). Investigations of water dissipation and WUE at the canopy level in fruit orchards began in the last century, and those results could play a more significant role in field water management practices.

The development of flux-monitoring procedures including eddy covariance method, the Bowen ratio–energy balance principle, and the large aperture scintillametre, among others, enabled evapotranspiration studies at the orchard-scale for kiwi plantations (McAneney et al., 1992; Judd et al., 1993), lemons (Daamen et al., 1999), olives (Testi et al., 2004; Ezzahar et al., 2007; Cammalleri et al., 2013), citrus (Rana et al., 2005), peaches (Paço et al., 2006a, 2006b; Qassim et al., 2013), bananas (Tanny et al., 2006), vines (Echeverría et al., 2012) and pineapples (José et al., 2007). In unsheltered northern New Zealand kiwi fruit orchards, evaporation flux is almost equal to the evaporative force (McAneney et al., 1992), but in kiwi orchards protected by fast-growing shelter belt trees,

* Corresponding authors. Tel.: +86 10 80794426; fax: +86 10 80794426.
E-mail addresses: guojiaxuangjx@163.com (J.-X. Guo), liyz-jie@163.com (Y.-Z. Li).

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WUE is only weakly dependent on the levels of solar radiation and water dissipation (Judd et al., 1993). In spite of these recent developments, there is a dearth of long-term systematic investigations into water dissipation and WUE at the orchard-scale. In the present study, we examined seasonal trends in water dissipation and WUE using the eddy covariance technique in no-tillage peach orchard with coarse sand in northern China over the whole period of fruit production.

2. Materials and methods

2.1. Site description

The study was performed between day of year (DOY) 207 in 2010 (July 26, 2010) and DOY 203 in 2011 (July 22, 2011) in a 135 ha peach orchard located northwest of Beijing (N 40°10′25.4″, E 116°07′53.6″; 61.7 m elevation above sea level). The orchard was on a piedmont alluvial plain at the intersection of the Taihang and Yanshan cordilleras. Fruits were the major arable produce in this region. This area has a continental, monsoonal, warm-temperate, semi-humid climate; the mean annual temperature is 11.9 °C; 74% of the 616 mm average annual precipitation falls in summer (June–August). There is very little precipitation during autumn, winter and spring (September–May). Frequent dry and windy weather in spring produces serious drought stress.

The experimental orchard was on flat terrain that had been planted with peach Trees 12 years previously. The soil was homogeneous and had a coarse sandy texture (11.0% clay, 3.0% silt, 82% sand, 4% gravel) at depths of 0–20 cm. Soil bulk density was 1.37 g kg^{-1}, organic matter content was 9.9 g kg^{-1}, and volumetric field capacity was 19.4%. The experimental area was approximately 300 m × 400 m and surrounded by orchards of peach trees. The density of peach trees at the experimental site was ca. 1250 ha^{-1}. The average height of the trees was 2.5 m. The orchard was maintained with natural grass mulch, but no tillage. The trees were watered with a traditional flooding irrigation procedure. The orchard was flooded (1800 mm ha^{-1}) before winter and during the bud-opening period.

2.2. Theory

An orchard's surface energy balance at the soil–atmosphere interface may be quantitatively described as follows:

$$R_n = H + \lambda E + G \tag{2.1}$$

$$A = R_n - G \tag{2.2}$$

where R_n is net radiation flux density (W m^{-2}), H is the sensible heat flux density (W m^{-2}), λE is the latent heat flux density (W m^{-2}), G is the soil heat flux density (W m^{-2}), and the available energy (A) is the difference between R_n and G (W m^{-2}). R_n and G are measured directly by instruments. λE, H and CO_2 flux density (F_C) are determined by the eddy covariance system, whose values are calculated as follows:

$$\lambda E = \lambda \overline{w' \rho_v'} \tag{2.3}$$

$$H = \rho_a C_p \overline{w' T'} \tag{2.4}$$

$$F_C = \overline{w' c'} \tag{2.5}$$

where w' (m s^{-1}), ρ_v' (g m^{-3}), T' (°C) and c′ (mg m^{-3}) are fluctuations in vertical wind velocity, water vapour, temperature and CO_2 concentration, respectively; ρ_a is air density (g m^{-3}); C_p is air specific heat at constant pressure (J kg^{-1} K^{-1}); and λ is the latent heat of water vapourisation (J g^{-1}).

WUE at the peach orchard canopy level may be represented by the ratio of net CO_2 exchange to actual evapotranspiration per unit land area. WUE was calculated on a daily basis as the ratio of daily F_C to daily evapotranspiration. Instantaneous WUE was calculated similarly, but using 30 min mean values rather than 24 h data, as follows:

$$\mathrm{WUE} = \frac{F_C}{ET_a} \tag{2.6}$$

where WUE was recorded at the canopy level (g CO_2 kg^{-1} H_2O), F_C is CO_2 flux density (mg $m^{-2} s^{-1}$) at the peach orchard canopy level, ET_a is actual evapotranspiration at the peach orchard canopy level (kg m^{-2} s^{-1}).

The evaporative fraction (EF) is the ratio of latent heat flux to available energy. It has been used to characterise the energy partition over land surfaces (Nichols and Cuenca, 1993) and is calculated as follows:

$$\mathrm{EF} = \frac{\lambda E}{A} = \frac{\lambda E}{R_N - G} \tag{2.7}$$

We determined these daily and seasonal characteristics of energy, water and CO_2 flux exchange between the peach orchard soil surface and atmosphere during the entire growth period, with particular focus on the periods after fruit harvest, after leaf fall, during flowering, during first fruit development, during the second fruit enlargement period and during fruit ripening.

2.3. Eddy covariance, micrometeorological and leaf area index measurements

CO_2, sensible heat, and latent heat fluxes of the peach orchard were measured 4.0 m above the ground by the eddy covariance method. We used a CO_2/H_2O infrared analyser (Li-7500; LI-COR, Inc., Lincoln, NE, USA) and a three-dimensional supersonic anemometer (CSAT-3; Campbell Scientific Inc., Logan, UT, USA) mounted on a horizontal bar extending from a tower. The observation site had a wide fetch of at least 500 m in all directions, which allowed us to neglect heat advection in the peach orchard. Short-wave and long-wave radiation from the sky and the land surface were measured with a net radiometer (CNR-1; Kipp and Zonen) 4.0 m above ground. Air temperature and humidity (data used in flux corrections) were measured with a temperature and relative humidity probe (HMP45C; Campbell Scientific Inc.). 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.) and self-calibrating heat flux sensors (HFP01; Campbell Scientific Inc.) buried 0.01 m below the soil surface at two different points; the averaged data were used in our analysis. Fluctuations in wind speed, sonic virtual temperature, and CO_2 and H_2O concentrations were sampled with the digital micrologger at 10 Hz. Details of instrumentation and measurement indices are listed in Table 1. WPL density correction was applied to fluxes of CO_2 and water vapour (Webb et al., 1980). Linear interpolation between values adjacent to missing or abnormal value(s) during rainy days was used for filling small gaps (2–3 half-hourly means missing) (Falge et al., 2001). Flux values were recorded in 30 min intervals with a data-logger (CR5000; Campbell Scientific Inc.) (Guo et al., 2012).

To estimate daily reference crop evapotranspiration (ET_0) using the FAO-Penman-Monteith methodology (Equation 6 in FAO-56, Allen et al., 1998), we measured a selection of climatic parameters (solar radiation, air temperature, relative humidity and wind speed). Solar radiation was measured with a total solar radiation sensor (LI-200X; LI-COR Inc.). Photosynthetically active radiation (PAR) was measured with an LI-190SB (LI-COR Inc.) sensor calibrated to the action spectrum of photosynthesis. Air temperature and humidity were measured 2.0 m above the ground using