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Hysteresis loops between canopy conductance of grapevines and meteorological variables in an oasis ecosystem

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ABSTRACT

Canopy conductance (g_c) is a key parameter that determines plant transpiration rate, and it is sensitive to multiple environmental variables. The relationships between g_c and micrometeorological variables still need to be investigated across a wide range of biomes and climatic conditions. In this study, sap flow, micrometeorological and biological factors for a vineyard at an oasis in Northwest China were measured from July to September in 2013 and 2014. Values of g_c were calculated from the simplified Penman–Monteith equation, and diurnal patterns of g_c were investigated in two study years. The relationships between g_c and main micrometeorological variables (global radiation *R*, vapor pressure deficit *D*, air temperature *T*) during the day exhibited hysteresis loops. By dividing daytime into three time periods, it was found that in the first period (7:00–11:00), stomatal opened quickly as *R*, *D* and *T* increase, so g_c increased positively to increasing *R*, *D* and *T*. In the second period (11:00–17:00), followed by stomatal closure, g_c decreased negatively to increasing *R*, *D* and *T*. In the third period (17:00–21:00), as stomatal aperture kept decreasing until sunset, g_c decreased positively to decreasing *R*, *D* and *T*. A simple linear model was used to simulate variations in g_c for the first period and the third period, and a negative logarithmic model was used for the second period. These models were consistent in predicting daytime variations in g_c. The results are useful in improving our current understanding of relationships between plant physiological and environmental processes in the oasis ecosystem.

1. Introduction

Plant transpiration (E_c) is a subject of increasing research interest (Lagergren and Lindroth, 2002; Buckley et al., 2012), especially in regions where transpiration is a fundamental datum in understanding the ecophysiology of plants (Chang et al., 2014). Jasechko et al. (2013) reported that transpiration is by far the largest water flux from earth's continents, representing 80–90% of terrestrial evapotranspiration (*ET*). Considering the dominance of E_c in continental *ET*, future changes in E_c will have significant impacts on global land temperatures and the fraction of precipitation entering rivers (Jasechko et al., 2013).

Canopy conductance (g_c) plays a key role in gas and energy exchanges across vegetated surfaces via their direct controls on CO_2 uptake and water losses (Alfieri et al., 2008; Berry et al., 2010; Damour et al., 2010; Ono et al., 2013). Therefore, studying the responses of g_c to the environmental variables is essential to understand the relationships between the plant physiological and environmental processes (Daly et al., 2004; Kumar et al., 2011; Ghimire et al., 2014). At present, g_c is usually calculated from the inverted Penman–Monteith (PM) equation based on data with sap flow method (Monteith, 1981; Granier et al., 2000a; Fernández et al., 2009; Kochendorfer et al., 2011; Ghimire et al., 2014). Sap flow method can provide direct and robust means of continuous measurement of water flux from trees (Granier et al., 1996, 2000a; Tang et al., 2006; Herbst et al., 2007, 2008; Nadezhdina et al., 2007, 2012), and provide mechanistic details on physiological and environmental controls of transpiration at the branch and whole plant level (Wilson et al., 2001). It is also well suited for determining species effects and other types of variability that occur in highly heterogeneous environments (Wullschleger et al., 2000; Wilson et al., 2001; Chang et al., 2014). Furthermore, measured sap flow data has been used successfully to derive values of g_c for varied vegetation

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types (Wullschleger et al., 2000; Motzer et al., 2005; Komatsu et al., 2012; Ghimire et al., 2014; Liu et al., 2015), and helps to understand g_c in regulating E_c in response to environmental condition changes (Ghimire et al., 2014). However, previous studies were mainly conducted in forest ecosystems (Oren et al., 1999, 2001; Ewers et al., 2005; Herbst et al., 2007, 2008; Fernández et al., 2009), detailed studies of fruit trees in oasis farmland ecosystems are relatively rare or nonexistent.

Canopy conductance (g_c) responds to multiple environmental variables (Damour et al., 2010). Previous studies often use midday data to quantify and simulate the responses of g_c to its influencing factors (Irvine et al., 2004; Herbst et al., 2008; Fernández et al., 2009; Kochendorfer et al., 2011; Zhang et al., 2012; Zhu et al., 2013; Hirano et al., 2014), morning and afternoon data were usually eliminated from their procedure due to low values in global radiation (R), vapor pressure deficit (D) or E_c (Granier et al., 2000b). Most studies found that g_c decreased with increasing D, and the relationship generally followed an exponential decay (Cienciala et al., 1992; Monteith and Unsworth, 1990; Oren et al., 1999; Motzer et al., 2005; Chang et al., 2006, 2014; Tang et al., 2006). While recently, Liu et al. (2015) reported that g_c was positively linear with D in a banana plantation in Northern Israel. Thus, the responses of g_c to environmental factors for different ecosystems still need to be carefully investigated, and it is urgent to catch a whole-day picture of the relationships between g_c and environmental factors.

Based on sap flow measurements and related micrometeorological and biological variables (i.e. leaf dimension, leaf area and leaf area index) in two study years, the specific objectives of this study were (1) to clarify diurnal courses of E_c and g_c of the vine canopy; (2) to examine relationships among E_c, g_c and main meteorological variables; (3) to quantify and model the daytime variations in g_c. By estimating the responses of g_c to main meteorological variables, this study is aimed to improve our understanding of the feed backs between the planted land surface and the atmosphere in the oasis farmland ecosystem.

2. Materials and methods

2.1. Site description

The experiment was conducted in Nanhu Oasis, Danghe river basin, Gansu Province, China (39°52′34″ N, 94°06′19″ E; 1300 m a.s.l), which belongs to a typical continental temperate zone. The study area has flat terrain, abundant sunlight with the annual total radiation between 5903.4 and 6309.5 MW m^{-2}, and convenient water resources from Wowa Lake, which is less than 2 km in the southeast. The annual average temperature and precipitation is 9.3 °C and 36.9 mm, respectively. The annual potential evapotranspiration is around 2400 mm (Ma et al., 2013). The soil type is Arenosols according to FAO classification, with a mean soil bulk density being 1.41 g cm^{-3}.

One vine plot (450 m × 160 m) was selected in the oasis to conduct our study. *Vitis vinifera* L. (cv. Thompson Seedless) grapevines were planted in rows at a spacing of 1 m between vines and 3 m between rows oriented north–south. The shoots were maintained on a vertical plane by three wires supported by a 2.5 m high T-trellis system. The root depth of the vines was about 1.0 m below the surface, which had no access to groundwater. The vineyard was furrow-irrigated every month during the growing seasons.

2.2. Environmental conditions and biological factors observation

Weather conditions were continuously monitored by an automatic weather station on site during the two study years. Rainfall was monitored by a tipping bucket rain gauge (TE525, Texas Electronics, USA). Global radiation (NR01, Hukseflux, Netherland) were measured at heights of 3 m above the ground. Both air temperature and relative humidity (HMP60, Vaisala, Finland) were measured at heights of 1, 1.5, 2, 2.5 and 3 m above the ground. Wind speed/direction (5103, R. M. Young, USA) were monitored about 0.5 m above the canopy. Soil water content (ML2x, Delta T, UK) was measured at 0.05, 0.1, 0.2, 0.5, 0.8 and 1 m depths. Half-hourly averages of the above data were computed and stored on a data logger (CR1000, Campbell, USA).

Leaf area index (*LAI*, LAI-2200, Li-Cor, USA) and leaf area were measured every 15 days on site. An allometric relationship between leaf length (cm), leaf width (cm) and leaf area (cm^2) was obtained (leaf area = 0.70 × leaf length × leaf width + 2.57, r^2 = 0.99), with the measurements of 150 leaves collected from the yard. Total leaf area (A, m^2) for each sample vine was then determined every month with measurements of all leaves. The average A showed narrow variation during study periods in two years, with values of about 3.62 ± 0.10 m^2 in 2013, and 3.65 ± 0.14 m^2 in 2014, respectively. Details about leaf area observation can be seen in Supplement.

2.3. Sap flow measurements

Six representative vines were selected every year with trunk diameters ranging from 1.97 to 4.14 cm, which covered most diameters of the vines in the yard. The heat balance method (Sakuratani, 1981) was used to measure sap flow (F, g h^{-1}) of grapevine with the Dynagage Flow 32A system (Dynamax, Houston, USA). To avoid water damage during irrigation, the gauges were installed at the height of more than 40 cm above the ground on trunk per vine. Details of the theory and installation can be seen in peers' work (Trambouze and Voltz, 2001). Gauge outputs were measured every 60 s and recorded as 30-min averages with a data logger (CR1000, Campbell, USA). Sap flow measurements were made between July 19 (DOY 200) and September 15 (DOY 258) in 2013, and between July 23 (DOY 204) and September 17 (DOY 260) in 2014.

2.4. Canopy transpiration (E_c) and canopy conductance (g_c)

Half-hourly canopy transpiration (E_c, mm h^{-1}) was calculated as (Soegaard and Boegh, 1995; Zhang et al., 2011):

$$E_c = \frac{k}{N}\sum_{i=1}^{N}\frac{F_i}{A_i} \times LAI \quad (1)$$

where k is used for units conversion (k = 0.001); N is the sampling number; F_i is sap flow of the ith individual (g h^{-1}); A_i is leaf area of the ith individual (m^2).

When calculating canopy conductance (g_c, mm s^{-1}), periods of rainfall and data obtained under the conditions of $R < 0$ and $D < 0.5$ kPa were excluded (Ewers and Oren, 2000). This is mainly because when R, D, and sap flow were close to zero, it will increase the relative inaccuracy in g_c calculation (Granier et al., 2000a). Half-hourly g_c was then calculated from E_c and meteorological data with the simplified PM equation (Monteith and Unsworth, 1990):

$$g_c = \frac{\lambda(T)E_c\gamma(T)}{\rho(T)C_pD} \quad (2)$$

where $\gamma(T)$ is the psychometric constant as a function of temperature (T, °C) (Pa K^{-1}), $\lambda(T)$ is the latent heat of vaporization of water (J kg^{-1}), E_c is transpiration (kg m^{-2} s^{-1}), C_p is the specific heat of air (J kg^{-1} K^{-1}), $\rho(T)$ is the density of liquid water (kg m^{-3}), and D is the vapor pressure deficit (Pa).

This equation could be applied based on the assumption that the studied canopy was well coupled aerodynamically (Phillips and Oren, 1998). To address this assumption, aerodynamic conductance (g_a, mm s^{-1}) was estimated according to Thom and Oliver