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Dynamics of evapotranspiration partitioning for apple trees of different ages in a semiarid region of northwest China

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ABSTRACT

Evapotranspiration in semiarid regions generally represents the greatest loss of water from an ecosystem and is sensitive to changes in the cover of vegetation. In this work, we compared the effects of apple tree of different ages by partitioning evapotranspiration into canopy interception (calculated), tree transpiration (thermal-dissipation probes) and soil evaporation (micro-lysimeter) in a semiarid region of northwest China from May to September in 2012, 2013 and 2014. Tree age had a clear influence on evapotranspiration partitioning. Daily transpiration and evapotranspiration were always higher for the 17- than the 7-year-old trees. Monthly canopy interception and transpiration of the 17-year-old trees were always higher, and monthly soil evaporation was always lower than the 7-year-old trees. Evapotranspiration was 339.1, 341.4 and 312.4 mm and 361.1, 367.2 and 336.3 mm for the 7- and 17-year-old trees in 2012, 2013 and 2014, respectively. Annual soil evaporation accounted for a large proportion of the evapotranspiration for the 7-year-old apple trees, ranging from 51.7 to 53.6%, and transpiration accounted for a large proportion of the evapotranspiration for the 17-year-old apple trees, ranging from 47.8 to 49.1%. Reference evapotranspiration was low during our experimental periods, and the relationship between actual evapotranspiration and reference evapotranspiration differed between the 7- and 17-year-old trees. Tree age was mostly responsible for the differences in evapotranspiration and its partitioning due to the morphologies of the trees. Tree age should therefore be taken into account when assessing the influence of evapotranspiration by apple trees on regional water budgets under our or similar climatic conditions.

1. Introduction

Semiarid northwest China is an important area of apple production due to its abundant sunlight, good ventilation and large diurnal temperature difference. The planting area and yield of apple trees in Shaanxi province are both the highest for China, and the apple industry has become the backbone of the rural economy and an important contributor to the national economy. This area has a dry climate and few available sources of water, so most crops are rainfed including apple trees (Chen et al., 2014).

Apple trees have high levels of transpiration, soil evaporation is intensive (Wang et al., 2012) and evapotranspiration consumes most of the rainfall (Li, 2001), so the conflict between water supply and demand is very serious and can have a negative effect on apple yield and quality (Naor et al., 2008). As the planted area continues to expand, the hydrological effect of the apple trees cannot be ignored, and the use of water for apple production is expected to change or modify the hydrology of the catchments. Studying the characteristics of water consumption in apple trees is thus necessary for sound planning of apple plantations with limited water resources, formulating scientific and reasonable management strategies and fully exploiting the productive potential of apple trees.

Most of the water lost in many arid and semiarid ecosystems globally is due to evapotranspiration (Noy-Meir 1973), often accounting for >95% of the annual water budget in semiarid ecosystems (Huxman et al., 2005; Wilcox et al., 2003; Williams et al., 2004). Evapotranspiration is an integrated term, composed of the

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precipitation intercepted by canopies, vapor fluxes of plant transpiration and soil evaporation (Raz-Yaseef et al., 2012). A number of measurement techniques such as catchment water balance (Bosch and Hewlett, 1982; Wilson et al., 2001), eddy covariance methods (Anderson et al., 2017; Baldocchi et al., 1988; Chávez et al., 2009; Ding et al., 2010; Er-Raki et al., 2009; Er-Raki et al., 2010), Bowen ratio energy balance systems (Denmead et al., 1993; Todd et al., 2000; Uddin et al., 2013), soil water balance (Cuenca et al., 1997; Jaeger and Kessler, 1997; Nicolas et al., 2005), lysimeters (Auzmendi et al., 2011; Liu and Luo, 2010) and sap flow (SF) methods (Cammalleri et al., 2013; Er-Raki et al., 2010; Green et al., 1997; Li et al., 2002; Smith and Allen, 1996) have been developed to measure evapotranspiration or its components. Partitioning evapotranspiration into its components is required to better understand the processes underlying the availability of water to trees and its response to change (Yepez et al., 2003). Canopy interception in vegetated areas is an important component of surface-water balance, particularly in semiarid areas (Wang et al., 2007) and has been the subject of many studies (Asdak et al., 1998; Klaassen et al., 1998; Licata et al., 2008; Link et al., 2004; Llorens and Gallart, 2000). Transpiration is the loss of water through foliar stomata (Rothfuss et al., 2010). Measurements of sap flow can provide mechanistic information at short timescales (Wullschleger et al., 2001) and are versatile because their applicability is not limited by complex terrain or spatial heterogeneity (Wilson et al., 2001). A method using thermal-dissipation probes developed by Granier (1987) can estimate whole-tree transpiration and has been particularly popular for identifying inter-tree variation in transpiration and for estimating stand transpiration due to its simplicity, reliability and low cost (Du et al., 2011; Licata et al., 2008; O'Brien et al., 2004; Peng et al., 2015; Ping et al., 2004). Soil evaporation comprises a significant part of the water budget in water-limited ecosystems (Raz-Yaseef et al., 2010). Soil evaporation is expected to be highly spatio-temporally variable (Villegas et al., 2010). Seasonal variations in the cover of deciduous woody species can strongly influence the dynamics of soil evaporation (Vivoni et al., 2008; Wilson et al., 2000). A micro-lysimeter method for determining evaporation from bare soil has been widely used in field experiment (Larsbo and Jarvis, 2006; Liu et al., 2002; Yunusa et al., 2004; Zhang et al., 2011).

The reference evapotranspiration (ET_0) is the largest possible evaporation of a reference surface under the condition of a sufficient underground water supply (Han et al., 2015). The measurement of ET_0 is necessary for the study of hydrology (Allen et al., 1998) and ET_0 is widely used to estimate the requirements of water for crops and for the analysis of ecological models (Xu et al., 2006). In this study, we assessed the components of evapotranspiration in 7- and 17-year-old apple trees, intercepted precipitation (calculated), tree transpiration (thermal-dissipation probes), soil evaporation (micro-lysimeter) and ET_0 (calculated by the Penman-Monteith formula) from May to September 2012, 2013 and 2014 in Changwu County on the Loess Plateau, focusing on the response of evapotranspiration and its partitioning with tree age. The objectives of this study were to: (1) evaluate and compare the dynamics of the components of evapotranspiration (canopy interception, soil evaporation and transpiration) for apple trees of different ages during the experimental cycle, (2) compare the effects of tree age on the contribution of each component to evapotranspiration, and (3) evaluate the agreement between calculated evapotranspiration and ET_0 for apple trees with different ages at daily scale.

This study will contribute considerably to our understanding of the partitioning of water consumption and evapotranspiration for apple orchards of different ages and will provide a scientific reference for estimating water consumption by apple trees in a semiarid region of northwest China.

2. Methods

2.1. Study area

The field study was conducted from May to September 2012, 2013 and 2014 at the Changwu Experimental Station of Northwest A&F University (107°40′–107°42′E, 35°12′–35°16′N; 1219 m a.s.l.) in the city of Xianyang, Shaanxi Province, northwest China. The study area is in the Wangdonggou watershed, where topographical characteristics are typical of loessial gullies. The watershed has a continental monsoon climate with seasonal monsoons, hot summers and cold winters and has an annual mean temperature of 9.1 °C, annual accumulated temperature (> 10 °C) >3029 °C, mean annual hours of sunshine >2230 h and frost-free period of about 171 days. Mean annual precipitation is 584 mm (mostly falling from July to September). Mean annual ET_0 is 1016 mm. Most of the apple trees (*Malus domestica*, cv. Fuji Apple) in the area were planted in 1996 and 2006 due to the influence of local government policy. The dominant tree ages in 2012 were thus 7 and 17 years. The experiments were conducted in two nearby orchards, one 7 years old and one 17 years old (Fig. 1). The environmental conditions for both orchards were thus assumed to be the same. The orchards were oriented east-west and were 70 m long and 16 m wide. Tree spacing within a row was 3.5 m, with 4.0 m between rows, for a density of 720 plants ha^{-1}. The orchards received similar annual pest and weed control and pruning, and the management practices were representative of the region. The orchards contained dark loessial soil. The groundwater table is below 50–80 m depth, and the mean dry bulk density in the upper 1.0 m of soil is 1.46 g cm^{-3}. The gravimetric field capacity is 21.1%, and the wilting point of soil water is 8.8%. Precipitation was the only source of water, and runoff from our study plots was negligible because both orchards were on a flat terrace.

2.2. Data set and calculation of ET_0

ET_0 was calculated from daily weather data for 2012, 2013 and 2014. The climatic variables included daily maximum and minimum temperature (Tmax and Tmin) at a height of 2 m, atmospheric pressure (AP), sunshine duration (N), maximum and minimum relative humidity (RHmax and RHmin) and wind speed (U_{10}) at a height of 10 m. The data was obtained from national meteorological stations which are located at the Changwu experimental station 300 m from the experimental orchards and maintained by the Chinese Meteorological Administration (http://cdc.cma.gov.cn).

Data for wind speed obtained at a height of 10 m was converted to speeds for the standard height of 2 m using a logarithmic wind-speed profile and conversion factor (Allen et al., 1998). Average monthly temperature and precipitation at the Changwu experimental station from 1985 to 2014 are presented in Table 1. We used the Penman-Monteith formula recommended by the Food and Agricultural Organization (FAO) to calculate daily ET_0 (mm d^{-1}) (Allen et al., 1998; Monteith, 1981; Penman, 1948). Daily ET_0 during the experimental periods in 2012, 2013 and 2014 is shown in Fig. 2.

2.3. Canopy interception

Canopy interception cannot be measured directly. It was calculated for each orchard by subtracting the sum of throughfall and stemflow from the daily incident precipitation measured by horizontally positioned tipping-bucket rain gauges installed in a clear grassy area 300 m from the orchards (Carlyle-Moses and Price, 1999). Daily rainfall and cumulative rainfall during the study periods in 2012, 2013 and 2014 are shown in Fig. 3. The frequency distribution of the rains (grouped into 10-mm intervals) and the