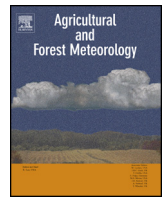




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## Evapotranspiration partitioning through in-situ oxygen isotope measurements in an oasis cropland

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### ABSTRACT

The oxygen isotope compositions of ecosystem water pools and fluxes are useful tracers in the water cycle. As part of the Heihe Watershed Allied Telemetry Experimental Research (HiWATER) program, high-frequency and near-continuous in situ measurements of  $^{18}\text{O}$  composition of atmospheric vapor ( $\delta_v$ ) and of evapotranspiration ( $\delta_{\text{ET}}$ ) were made with the flux-gradient method using a cavity ring-down spectroscopy water vapor isotope analyzer. At the sub-daily scale, we found, in conjunction with intensive isotopic measurements of other ecosystem water pools, that the differences between  $^{18}\text{O}$  composition of transpiration ( $\delta_T$ ) and of xylem water ( $\delta_x$ ) were negligible in early afternoon (13:00–15:00 Beijing time) when ET approached the daytime maximum, indicating isotopic steady state. At the daily scale, for the purpose of flux partitioning,  $\delta_T$  was approximated by  $\delta_x$  at early afternoon hours, and the  $^{18}\text{O}$  composition of soil evaporation ( $\delta_E$ ) was obtained from the Craig-Gordon model with a moisture-dependent soil resistance. The relative contribution of transpiration to evapotranspiration ranged from 0.71 to 0.96 with a mean of  $0.87 \pm 0.052$  for the growing season according to the isotopic labeling, which was good agreement with soil lysimeter measurements showing a mean transpiration fraction of  $0.86 \pm 0.058$ . At the growing season scale, the predicted  $^{18}\text{O}$  composition of runoff water was within the range of precipitation and irrigation water according to the isotopic mass conservation. The  $^{18}\text{O}$  mass conservation requires that the decreased  $\delta^{18}\text{O}$  of ET should be balanced by enhanced  $\delta^{18}\text{O}$  of runoff water.

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### 1. Introduction

Heihe River, the second longest inland river of China, is located in the continental arid climate in the inland region of northwest China, in the transition zone between the westerlies and the southwest (summer) monsoon (Huang and Wen, 2014; Guo et al., 2015). The oasis agriculture in the middle and lower reaches of the Heihe River Basin is supported by the precipitation and snowmelt from the Qilian Mountains, where Heihe River originates (Yang et al., 2015). Water conservation is a top priority for scientific research. Vegetation transpiration (T), through the stomata of plants and associated with plant productivity, and soil evaporation (E), not directly contributing to production, are the two components of evapotranspiration (ET). Research on the partitioning of ET in this region is of great interest to water resource managers. In addition,

data on E and T are needed for validation of ecosystem models. Because E and T are controlled by different processes, the ability to separate ET into its components should improve the prediction of climatic responses of ecosystem functions and processes and our understanding of surface-atmosphere water and energy exchange (Li et al., 2013; Kool et al., 2014; Sutanto et al., 2014).

Although partitioning of ET has been performed for decades, using either isotopic or non-isotope approaches, the accuracy of the partitioned fluxes is still not satisfactory (Kool et al., 2014; Sutanto et al., 2014). The sources of errors mainly include assumption used in the analyses and instrument inaccuracy (Sutanto et al., 2014). In isotope-based approaches, water vapor fluxes produced by soil evaporation and plant transpiration have different oxygen and hydrogen isotope compositions because soil evaporation is much more fractionated than plant transpiration. The isotopic end-member difference provides the basis for ET partitioning (Yakir and Sternberg, 2000). Most partitioning studies focus on forest (Moreira et al., 1997; Wang and Yakir, 2000; Yezpe et al., 2003, 2007; Williams et al., 2004; Lai et al., 2006; Robertson and Gazis,

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2006; Xu et al., 2008; Dubbert et al., 2014b; Sun et al., 2014) and grassland ecosystems (Ferretti et al., 2003; Yezpey et al., 2005; Wenninger et al., 2010; Sutanto et al., 2012; Dubbert et al., 2013; Hu et al., 2014), but few studies have been performed on cropland ecosystems (Wang and Yakir, 2000; Zhang et al., 2011). An advantage of cropland systems is that conventional non-isotope methods for the ET partitioning, such as the combination of micro-lysimeters to measure evaporation and eddy covariance to measure evapotranspiration (Kool et al., 2014; Sutanto et al., 2014), can be implemented to check the isotopic results. However, the micro-lysimeters have drawbacks of inability to measure during irrigation or rain, time consuming, and limited representation due to small sample size (Kool et al., 2014).

Combined with the eddy covariance technique, measurement of the oxygen isotope compositions of ecosystem water pools and fluxes can be used to partition the ET flux into its component fluxes. A key challenge is to precisely determine the  $^{18}\text{O}$  composition of ET ( $\delta_{\text{ET}}$ ) (Yakir and Sternberg, 2000; Sutanto et al., 2014). At the present time, most investigations have used the Keeling mixing model to infer  $\delta_{\text{ET}}$  indirectly (Wang and Yakir, 2000; Williams et al., 2004). The Keeling method is unreliable for water vapor because of a large entrainment effect caused by strong gradients in the vapor isotope composition across the top of the atmospheric boundary layer (Lee et al., 2012). Other limitations of the Keeling method to water isotopes include the assumption that the isotopic composition of the evaporation and transpiration do not change during the measurement interval (typically 30–60 min), the loss of water vapor from the ecosystem only by turbulent mixing, and the varied concentration of atmospheric water vapor only resulting from background vapor and local evapotranspiration (Lee et al., 2007; Hu et al., 2014; Sutanto et al., 2014).

The second challenge is how to best capture dynamic variations of the  $^{18}\text{O}$  composition of transpiration ( $\delta_{\text{T}}$ ). To date,  $\delta_{\text{T}}$  can be determined with four approaches. In isotopic steady state (ISS),  $\delta_{\text{T}}$  is equal to the isotopic composition of plant source water and can be derived from direct measurements of xylem water ( $\delta_{\text{x}}$ ) (e.g., Moreira et al., 1997; Williams et al., 2004). In nonsteady state conditions,  $\delta_{\text{T}}$  can be estimated by models such as the Craig-Gordon (Craig and Gordon, 1965), the Dongmann (Dongmann et al., 1974), and the Farquhar-Cernusak model (Farquhar and Cernusak, 2005). In addition,  $\delta_{\text{T}}$  can be also directly measured with leaf and branch chambers (Wang et al., 2010; Dubbert et al., 2014a). Finally,  $\delta_{\text{T}}$  can be calculated from the isotopic mass balance using measurement of the foliage water pool changes over time (Hu et al., 2014). The ISS assumption is frequently used in flux partitioning studies. However, model results demonstrate that ISS is only met for short (hourly) timescales at noon or in early afternoon (Welp et al., 2008). Few studies have evaluated the ISS assumption via water pool and flux measurements (Hu et al., 2014).

The third challenge is related to quantification of the  $^{18}\text{O}$  composition of evaporation ( $\delta_{\text{E}}$ ). Generally,  $\delta_{\text{E}}$  is calculated with the Craig-Gordon model (Craig and Gordon, 1965; Yezpey et al., 2003; Williams et al., 2004; Hu et al., 2014), whose input variables include the isotopic composition of soil water at the evaporation front, isotopic composition of water vapor ( $\delta_{\text{v}}$ ), relative humidity, and equilibrium and kinetic fractionation factors. The model calculation is most sensitive to  $\delta_{\text{v}}$  and the determination of soil evaporation front (Sutanto et al., 2014). The endmember  $\delta_{\text{E}}$  can be also measured directly with soil chambers (Dubbert et al., 2013, 2014b).

Over the last several years, isotope ratio infrared spectroscopy (IRIS) has permitted high-frequency and near-continuous in situ measurements of atmospheric  $\delta_{\text{v}}$  (Lee et al., 2005; Wen et al., 2008, 2012b; Griffis, 2013), providing an attractive alternative to the traditional method involving collection of samples with cold traps and subsequent measurement by isotope ratio mass spectrometry (IRMS) (Helliker et al., 2002). The  $\delta_{\text{v}}$  measurements of most

previous studies (i.e., cold traps) are discrete and labor intensive (Moreira et al., 1997; Wang and Yakir, 2000; Yezpey et al., 2003; Xu et al., 2008). Advances in measuring the atmospheric  $\delta_{\text{v}}$ , together with the flux-gradient or eddy covariance technique, enables to quantification of  $\delta_{\text{ET}}$  (Wen et al., 2012a; Huang and Wen, 2014). To date, only a few studies have deployed  $\delta_{\text{ET}}$  measured with the micrometeorological methods for ET partitioning (Lee et al., 2007; Hu et al., 2014).

This study is concerned with the partitioning of ET into its components of E and T in an irrigated cropland. The experiment was conducted as part of the Heihe Watershed Allied Telemetry Experimental Research (HiWATER) program (Li et al., 2013). The  $^{18}\text{O}$  signals of the three flux endmembers ( $\delta_{\text{ET}}$ ,  $\delta_{\text{E}}$  and  $\delta_{\text{T}}$ ) were determined during the growing season of a maize crop, in the middle reaches of Heihe River Watershed in 2012 using the flux gradient approach. The specific objectives of this study are: (1) to characterize, in conjunction with intensive measurements of  $^{18}\text{O}$  composition of the ecosystem water pools, isotopic steady state using isotopic mass balance at the sub-daily scale, (2) to characterize the temporal dynamics of the  $^{18}\text{O}$  signals of ET, E and T at the daily to seasonal scale, and quantify the contribution of T to ET using isotopic labeling and lysimeter measurements.

## 2. Materials and methods

### 2.1. Site description

The study site in Zhangye, Gansu Province was part of the Heihe Watershed Allied Telemetry Experimental Research (HiWATER) program (Li et al., 2013). This sites had good fetch (>200 m). The experiment was conducted in an arid artificial oasis spring maize in the middle reaches of the Heihe River Watershed (38°51'N, 100°22'E, 1550 m asl) in northwest China. Over the past five decades (1961–2010), the daily mean temperature was 7.4 °C and the mean annual precipitation was 128.7 mm. The experiment was conducted from May 27 to September 22 (DOY 148–265) in 2012. Plastic films were used for water conservation, covering rate about 60% of the soil surface. Flood irrigation water was applied four times (DOY 158, 184, 210 and 238) during the growing season. Spring maize was planted on April 20 and harvested on September 22, 2012. The maximum LAI and maximum canopy height were 5.6 m<sup>2</sup> m<sup>-2</sup> and 2.1 m, respectively. Additional details concerning site information and data acquisition are described by Huang and Wen (2014) and Yang et al. (2015).

### 2.2. In-situ measurement of water vapor and evapotranspiration isotope ratios

The isotopic composition of water vapor in surface air ( $\delta_{\text{v}}$ ) was measured using a cavity ring-down spectroscopy (CRDS) water vapor isotope analyzer (Model L1102-i, Picarro Inc.). The schematic diagram of the CRDS analyzer, its principle of operation, and its calibration procedure were described in Huang and Wen (2014). Briefly, air was pumped from two heights above the crop through heated tubes to the analyzer for analysis. The heights of the two intakes were 0.5 and 1.5 m higher than the canopy and increased over the season from 0.6 m and 1.6 m above the ground at the beginning to 2.6 m and 3.6 m by the end of the maize season to adjust for canopy growth. The air samples were pumped through the analyzer sequentially with 120 s spent on each measurement. The step changes in the H<sub>2</sub>O, H<sub>2</sub><sup>18</sup>O and H<sub>2</sub><sup>16</sup>O mixing ratios in response to valve switching between two air sample intakes are given in Fig. 1, indicating that the measurement approached steady state in less than 30 s after each switching. For safety, 10 data points (~50 s) after switching was discarded in this study. The

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