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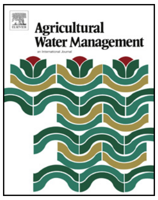

Partitioning of evapotranspiration using a stable isotope technique in an arid and high temperature agricultural production system

Xuefei Lu[a], Liyin L. Liang[b], Lixin Wang[a,*], G. Darrel Jenerette[c], Matthew F. McCabe[d], David A. Grantz[c]

[a] Department of Earth Sciences, Indiana University-Purdue University Indianapolis (IUPUI), Indianapolis, IN 46202, United States
[b] School of Science, University of Waikato, Hamilton, New Zealand
[c] Department of Botany & Plant Sciences, University of California Riverside, Riverside, CA 92521, United States
[d] Water Desalination and Reuse Center, Division of Biological and Environmental Sciences and Engineering, King Abdullah University of Science and Technology, Thuwal, Saudi Arabia

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ABSTRACT

Agricultural production in the hot and arid low desert systems of southern California relies heavily on irrigation. A better understanding of how much and to what extent irrigated water is transpired by crops relative to being lost through evaporation would improve the management of increasingly limited water resources. In this study, we examined the partitioning of evapotranspiration (ET) over a field of forage sorghum (*Sorghum bicolor*), which was under evaluation as a potential biofuel feedstock, based on isotope measurements of three irrigation cycles at the vegetative stage. This study employed customized transparent chambers coupled with a laser-based isotope analyzer to continuously measure near-surface variations in the stable isotopic composition of evaporation (E, δ_E), transpiration (T, δ_T) and ET (δ_{ET}) to partition the total water flux. Due to the extreme heat and aridity, δ_E and δ_T were very similar, which makes this system highly unusual. Contrary to an expectation that the isotopic signatures of T, E, and ET would become increasingly enriched as soils became drier, our results showed an interesting pattern that δ_E, δ_T, and δ_{ET} increased initially as soil water was depleted following irrigation, but decreased with further soil drying in mid to late irrigation cycle. These changes are likely caused by root water transport from deeper to shallower soil layers. Results indicate that about 46% of the irrigated water delivered to the crop was used as transpiration, with 54% lost as direct evaporation. This implies that 28 – 39% of the total source water was used by the crop, considering the typical 60 – 85% efficiency of flood irrigation. The stable isotope technique provided an effective means of determining surface partitioning of irrigation water in this unusually harsh production environment. The results suggest the potential to further minimize unproductive water losses in these production systems.

1. Introduction

Agriculture is the largest single user of fresh water globally, accounting for approximately 70% of the total withdrawn for human consumption (Hoekstra and Mekonnen, 2012; Wada et al., 2014). In the United States (US), irrigated agriculture is the second largest primary user of fresh water, accounting for 31% of the developed water resource (Vörösmarty et al., 2000). The Imperial Valley, in the low elevation desert of southern California, a region characterized by extreme heat and evaporation, has been considered a promising area for biofuel feedstock production (Oikawa et al., 2015). This area produces more than two-thirds of winter vegetables consumed in the US and about three-quarters of summer hay and other field crops in southern California (Medellín-Azuara et al., 2012). At present, there is a lack of data addressing the sustainability, including water use efficiency, of biofuel production in this high temperature agricultural site.

The Colorado River is a key source of water for California's irrigated desert agriculture, accounting for approximately one-third of annual flow (Cohen et al., 2013). A growing demand for water, coupled with the limited supplies and impacts of climate change (Vörösmarty et al., 2000), have placed enormous pressures on California's water supply. Recent years of drought have exacerbated this water scarcity challenge, especially in the Imperial Valley.

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* Corresponding author.
E-mail address: lxwang@iupui.edu (L. Wang).

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Evapotranspiration (ET) represents one of the largest components of the global water cycle, with approximately 65% of precipitation returned to the atmosphere via ET at the global scale (Trenberth et al., 2007). However, ET loss can reach up to 95% in some dryland systems (Wang et al., 2014; Wilcox and Thurow, 2006). Evapotranspiration consists of two distinct components: evaporation from soil and plant surfaces (E) and transpiration taken up by roots and lost through stomatal pores (T). These two components are controlled by different processes and have different water use implications. Transpiration is mainly controlled by atmospheric evaporative demand and soil water status, and modified by plant physiological controls on leaf stomata. Because photosynthetic carbon dioxide fixation is concurrent with water vapor loss, and shares the stomatal diffusion pathway, irrigated water transpired by crops is productive in that it facilitates photosynthesis and leads to leaf cooling. Evaporation from soil, in contrast, is not directly linked to biological processes, but rather results from diffusion of water through the soil matrix and evaporation at the surface, and is controlled solely by physical factors. Although it may lead to local evaporative cooling, this water loss is not directly linked to biological productivity. Because of the different controlling mechanisms, E and T are likely to have different responses to environmental drivers such as temperature and soil water content (Kool et al., 2014; Wang et al., 2014). As competition for available irrigation water increases, a better understanding of how much is transpired relative to that lost through evaporation, and the factors controlling this partitioning, could contribute to improved water resource management (Wang and D'Odorico, 2008).

Separating E and T has proven to be difficult. Various methods have been proposed, including empirical measurements and modeling-based approaches. Empirical measurements can include lysimeters, large tree potometers, whole tree chambers, eddy covariance measurements of above- and below-canopy fluxes, upscaling of sap-flow measurements, and flux-variance similarity partitioning, as well as using stable isotopes (Kool et al., 2014). Modeling approaches include the FAO-56 dual crop coefficient model (Ding et al., 2013), modeling of canopy and subcanopy fluxes driven by energy balance measurements (Ershadi et al., 2014; Kalma et al., 2008) or combining process-based modeling and isotope tracer measurements (Cai et al., 2015; Wang et al., 2015). The recent development of techniques using stable isotopes of water have provided a useful tool to separate E and T, that can be applied across broad spatial and temporal scales. Besides facilitating ET partitioning, the stable isotopic composition of E and T can also provide insights regarding plant water use dynamics as well as the nature of land-atmosphere interactions (Parkes et al., 2016).

The basis for using the isotopes of H and O in water to partition ET is that evaporation significantly fractionates the surface soil water, enriching the source with the heavier isotopes, while transpiration does not lead to fractionation when T is large (Wang et al., 2012; Wang et al., 2013). Therefore, the isotopic composition of transpiration (δ_T) remains similar to the isotopic composition of the plant source water, while the isotopic composition of evaporated water differs from that of the source. This results in distinct isotopic signatures of δ_E and δ_T (Wang et al., 2013; Zhang et al., 2011).

The development of field-deployable laser-based instruments with similar precision to traditional isotope ratio mass spectrometers (e.g., Wang et al., 2009), has provided a promising tool to separate T from E in agricultural systems (Wang et al., 2012; Wang et al., 2013). The application of such methods to direct measurement of the isotopic composition of E, T and the combination, ET, in a hot, arid agricultural production system has not previously been attempted.

The objectives of the current study are to: (1) use a laser-based isotope analyzer and customized T, E and ET chambers to measure the respective isotope signatures, δ_T, δ_E, and δ_{ET}; (2) combine the estimates of δ_T, δ_E, δ_{ET} and total ET to partition the evaporative flux and to quantify the fraction of irrigation that is partitioned to productive T in this sorghum production system. These measurements provide important information for regional water issues, for crop management scenarios, and offer substantial insight into currently temperate production systems that may become warmer.

2. Materials and methods

2.1. Study site

The study was conducted at the University of California's Desert Research and Extension Center (DREC) located in the Imperial Valley, southern California (32.867°N 115.448°W) (Fig. 1a). This area is an interior desert valley about 18.3 m below sea level. The weather represents a desert climate with over 350 days of sunshine. The nearest automatic weather station (Meloland, 32.806°N 115.446°W) is managed by the California Management Information System (CIMIS) (http://www.cimis.water.ca.gov). Routine meteorological variables, including solar radiation, wind, humidity, air temperature, precipitation and soil temperature, as well as reference ET (ET_o), have been recorded hourly since December 1989. The mean annual precipitation from 1990 to 2015 was 80.3 mm year^{-1}, while the mean annual ET_o reaches 1846 mm year^{-1} (Fig. 1b). Most of the rainfall occurs in late summer, with June being the driest month (Fig. 1b). The mean annual temperature is 22.4 °C with a monthly mean temperature of 12.6 °C in January and 32.9 °C in August (for the period 1990–2015) (Fig. 1c). The mean annual relative humidity of the study area is around 46% (Fig. 1d). The experimental field has been used for agricultural production since the establishment of DREC in 1912. Irrigation water is supplied through the All-American Canal, distributed by gravity from the Colorado River. Irrigation is provided by regularly scheduled flooding of furrows. Soils in the regions are moderately to well-drained deep alluvial soils (42% clay, 41% silt 16% sand) with sub-surface drainage tile, and pH of 8.3 (Oikawa et al., 2014).

The *Sorghum bicolor* (cv. Photoperiod LS; Scott Seed Inc.) was planted in February 2012 for biofuel production, and was cut three times each year at the end of the vegetative stage. Ten extensive field measurements of δ_T, δ_E and δ_{ET} were conducted on July 24, 26, 28, 30 and August 4, 6, 7, 13, 18 and 20, 2014. Measurements covered the three irrigation cycles of one of the three vegetative harvests obtained each year. Plants were harvested for biomass before substantial flowering had occurred, and thus remained in the vegetative stage throughout the experiment. The irrigation events occurred on July 22, July 31 and August 9, 2014, each lasting 24 h. Isotope sampling was conducted one full day after irrigation to allow for drainage. There were two minor rainfall events during the measurement period, with a total rainfall of 1.27 mm. The mean monthly air temperature was 33.5 °C and 31.9 °C in July and August 2014.

2.2. Isotope-based partitioning

The technique developed by Wang et al. (2012, 2013) was modified to fit our specific needs. The isotopic compositions of the three component vapor fluxes (δ_T, δ_E and δ_{ET}) were directly quantified using a field deployable Triple Water Vapor Isotope Analyzer (T-WVIA, Los Gatos Research, Inc., Mountain View, CA, USA). Samples were obtained using customized transparent acrylic chambers containing circulation fans and directly linked as a closed system with the T-WVIA. δ_T was measured at 1 Hz with a customized leaf chamber ($2 \times 4 \times 12$ cm) having leaves sealed inside the chamber for 1–2 min. The δ_E and δ_{ET} were measured using a larger customized

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