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Rainwater use by irrigated cotton measured with stable isotopes of water

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ABSTRACT

The natural rate of recharge for some groundwater systems, such as the Southern Ogallala Aquifer in the central United States, is smaller than the rate of annual withdrawals for irrigation. As aquifer depletion continues, efficient management of the water budget gains importance. Of interest is the use of rainwater by irrigated crops during the course of the growing season, as rain can account for an important amount of the water input in the semi-arid climate of the Texas High Plains. We tested the suitability of stable isotopes of water as a method to determine the source of water in the transpiration of field-grown cotton (*Gossypium hirsutum* L.) plants from either rain or irrigation-water. We selected this method because irrigation water from the Ogallala Aquifer has a stable isotopic signature that can either be enriched or depleted when compared to the isotopic signature of water from any rain event. Cotton petioles were sampled before two rain events of 33 mm, and after every 2 h for two days. The water in the cotton petioles was extracted using cryogenic vacuum distillation and was analyzed for its isotopic signature. The results showed a shift of 29% from −7 (‰) to −5 $\delta^{18}O$ (‰), which is similar to the isotopic signature of the rainwater (−4.2 $\delta^{18}O$ (‰)). These results suggest that it is possible to use water stable isotopes to differentiate between rainwater and irrigation transpired by cotton under field conditions.

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1. Introduction

While only 17% of the global agricultural land is irrigated, the irrigated portion accounts for approximately 40% of the global food production (Gleick, 2003; Abdullah, 2006; Rost et al., 2008; Wada et al., 2012) and 70% of developed water supplies are delivered to agriculture (Shiklomanov, 2000; Doll et al., 2009; Siebert and Döll, 2010). Further, of the total water used globally for irrigation, it is estimated that 20% is extracted from nonrenewable groundwater sources (Wada et al., 2012). The demand for irrigation water has more than tripled from the 1960s through 2000 and demand will continue to increase as the global population increases (Wada et al., 2012).

The Ogallala Aquifer extends over 450,000 km^2 of the Great Plains area of the United States (http://water.usgs.gov/ogw/aquiferbasics/ext_hpaq.html). The aquifer underlies eight states and is the primary source of irrigation water in the region. For example, in the 1900s the Ogallala aquifer accounted for 27% of the irrigated land (Darton, 1898) and more recently this share increased to 32% in the United States (Gollehon and Winston, 2013). Depths to water table measurements taken over several decades have documented the continued depletion of the aquifer. The mining of the aquifer will likely lead to a shift in land use in the Texas High Plains from irrigated production to either deficit irrigation or to dryland production or even possibly reverting to its original condition of rangeland (Norwood and Dumler, 2002; Colaizzi et al., 2009). Deficit irrigation is a strategy whereby crops are deliberately allowed to endure some degree of water stress by not applying water to meet the requirement of the crop (English et al., 1990). Dryland refers to agricultural systems that exclude irrigation and are associated with water conservation, and limited input of fertilizers (Steiner et al., 1988; Stewart et al., 2006).

In production agriculture, for both deficit-irrigated and dryland-cropping systems, the efficient use of inputs to the water budget increasingly becomes important. For example, in the semiarid climate of the Texas High Plains, inputs to the water balance include irrigation and rainwater. However, the rainwater portion varies from year-to-year, is unpredictable and can represent a small portion of the input, as documented by the many droughts that occur in this area, e.g., Woodhouse et al. (2002), Schubert et al. (2004), and Scanlon et al. (2012). On average, the area surrounding

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Lubbock TX receives an annual rainfall of 474 ± 144 mm per year with most of the rain falling during the growing season (Lascano, 2000; Holman et al., 2014). The monthly coefficient of variation of rainfall is >70% and about 50% of the rain events during the growing season are <10 mm (Mauget and Leiker, 2010). The rain events are typically characterized by isolated thunderstorms that move quickly with high rates of short duration. The majority of this summer precipitation derives from Gulf of Mexico air masses and the winter precipitation is from air masses from the eastern Pacific Ocean (Nativ and Riggio, 1989). During the growing season and for rain events of <10 mm, we hypothesized that a large portion of this water evaporates from the soil surface (*E*) and thus only a small amount, if any, will be transpired by the crop (*T*). Further, if the crop experiences frequent droughts it will not have active roots near the soil surface (0–0.1 m) to uptake the water that remains in the soil after *E*. When calculating the seasonal water balance of a crop, small rain events contribute to *E* but not to *T*. Thus, the importance of partitioning evapotranspiration (*ET*) into its two components *E* and *T* (Lascano et al., 1987; Lascano and Baumhardt, 1996).

While several methods exist to track the root-uptake of water in plants, there are few that will differentiate between sources of water used by a plant under field conditions. One such method is stable isotopes, which has been used in ecology to study water movement through different environments and for several decades (Dawson et al., 2002; Flanagan et al., 2005) and has been used to partition *ET* into *E* and *T* (Chimner and Cooper, 2004; Rothfuss et al., 2010).

There have been several studies on the movement of water in plants including cotton using stable isotopes. These studies have mainly focused on leaf tissue and on understanding the enrichment of pore water at the stomates or the movement of water from the veins to the stomates (Gan et al., 2002; Barbour et al., 2004; Wang et al., 2012). These types of studies require using controlled laboratory conditions with plants grown in the greenhouse to observe isotopic changes in the leaf water. Research has also been done investigating the isotopic fractionation of soil water during evaporation in the soil profile by studying sand columns (Allison, 1982; Braud et al., 2009). Again most of these studies have been done in the laboratory with a few studies done in field conditions, i.e., sand dunes in Australia as well as Africa (Barnes and Allison, 1988; Sharma and Hughes, 1985). There has been little work done at the field scale under production conditions to try to observe changes in isotopic composition of plant water caused by smaller rain events that can add up to be a large portion of the water budget over the course of a growing season. Our objective was to determine if the *T* that originates from rain events, which have a different isotopic signature than irrigation water from the Ogallala Aquifer, could be measured using stable isotopes of water under dryland and deficit irrigated conditions.

2. Materials and methods

2.1. Site description

The experiments were conducted at the United States Department of Agriculture (USDA) – Agricultural Research Service (ARS), Cropping Systems Research Laboratory in Lubbock, TX (33.59°N, 101.89°W and average elevation of 960 m above sea level). Soil and plant samples were taken from an irrigated field with a center pivot and from field-plots irrigated with subsurface drip with an adjacent dryland plot. The soil of all sampled plots is classified as an Amarillo soil series (fine-loamy, mixed, superactive, thermic Aridic Paleustalfs) with soil physical properties given by Baumhardt et al. (1995). The climate of the Texas High Plains is semi-arid with an erratic rainfall distribution during the growing season, and is characterized by days with, low air humidity, and high wind speed and solar irradiance.

Cotton (FiberMax[2] 9180B_2F, Bayer CropScience, Research Triangle Park, NC) was planted on 1 May 2012 (Day Of Year, DOY 122) in the sub-surface drip and dryland fields, and 7 May 2012 (DOY 128) in the center pivot field. The center pivot (Zimmatic™, Omaha, NE) was 110-m long with two spans, covering about 4 ha, and applied 25 mm of water every 3 days. The sub-surface drip irrigation consisted of 22-mm flexible drip tubing (Eurodrip®, Madera, CA) installed between alternate 1.0-m rows (2.0 m between drip tapes) with the tape buried 0.30 m below the soil surface. The emitters on the drip tape were spaced 0.6 m apart and the cotton was irrigated daily with 3 mm.

2.2. Experimental overview

To discriminate between the changes in isotopic signature of the plant due to *T* of rainwater from simple diurnal variation in the isotopic conditions of the plant, several factors must be considered. One is the diurnal variation in the isotopic signature of different plant tissues. Another is the variability in isotopic signature based on spatial variability, e.g., variation in soil water. To minimize diurnal variation in isotopic signatures in the plant, tissues that represent points of isotopic fractionation, plant leaves, were avoided and petioles were chosen (Yakir et al., 1990). To maintain some systematic plant height conditions, meristematic petioles were chosen so that all plant tissue sampled was from the top of the plant and the canopy was considered uniform in height.

To address spatial and diurnal variability over a 24-h time period an evaluation of the soil and plant water isotopic conditions was conducted on 6 August 2012 (DOY 219) following a 28-day period with no rain before and during sampling. Spatially random sampling of the cotton meristematic petioles was used to observe variability in the isotopic signature of the plants in a field-plot. Here, two cotton samples were taken at every time-period to provide redundancy in case of a loss of a sample due to vials breaking or problems during extraction of the sample that could cause loss of a data point. Hence, two samples were taken at random across the field and where possible both samples were analyzed. The resulting two samples were considered independent of each other and were not averaged, and provided a measure of the variability of the isotopic signature across each field at a particular time (Flanagan et al., 2005).

This first evaluation was considered a “control” and was used to quantify the variation in isotopic composition of plant and soil water samples, over a 24-h period, obtained from the dryland, and drip and center pivot irrigated fields. However, due to drought conditions, there was only one day, 13 September 2012 (DOY 257), that had two rain events, 27.4 and 6.4 mm, which was used to obtain soil and plant samples from the center pivot, drip irrigated and dryland fields. Hereafter, this is referred to as the “rain event”.

2.3. Petiole sample collection, extraction and analysis

Prior to any rain, three meristematic petiole samples were taken from cotton plants randomly distributed in a 10 m × 20 m area of each field. As described in Section 2.2, two petiole samples were taken every time. The length of the petioles were reduced in size to 5 mm and placed in glass vials and sealed. The vials were then placed in a laboratory freezer until extraction of the plant water could be conducted. On 14 September 2012 (DOY 258), after the second rain of 6.4 mm, cotton petiole samples were taken, as

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