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Dynamics of water uptake by maize on sloping farmland in a shallow Entisol in Southwest China

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ABSTRACT

The water use patterns of maize grown in shallow soils remain poorly understood. To explore the water uptake dynamics of maize from a loamy Entisol with an average thickness of 40 cm, excavation, isotopic tracer analysis and soil water potential measurements were combined to study the source of water used by maize. The differences between the δD of the water used by maize and the δD of the mobile soil water (MSW, the fraction of soil water with high mobility which can be easily replaced by the infiltrating rainwater) indicated that maize did not take up much MSW. The local meteoric evaporation line, the δD of the bulk soil water (BSW, total soil water including mobile and immobile soil water) and the soil water collected using a lysimeter were used in a model to calculate the isotopic compositions of different fractions of soil water and the proportion of immobile soil water (ImSW, the fraction of soil water with little mobility which was tightly bound to the soil particles). ImSW resulted from several heavy rains that occurred before the sampling. The primary water sources for maize varied temporally and spatially. Maize seedlings at the one-leaf stage used ImSW from 0 to 10 cm soil depth; however, maize plants generally used more BSW from deeper soil layers when the roots reached greater depths. The ratios of MSW to ImSW were not equal between the maize stems and soil, with more ImSW in the maize stems, particularly during the seedling stage. This result invalidates the core concept of most watershed hydrology models and classical hypothesis in the isotopic models of general atmospheric circulation. The difference between the MSW and ImSW in the water cycle of the soil-plant-atmosphere continuum should be considered in the future studies of identifying the plant water sources and modeling hydrological processes.

1. Introduction

It is important to clarify how crops use various water sources to understand the soil- plant- atmosphere continuum (SPAC) hydrological cycle in a given agricultural system. The variation and ecological plasticity of the water-uptake depth by plant is an important means of evaluating the vegetation controlling of the hydrological balance in agricultural landscapes (Asbjornsen et al., 2008; Zhang et al., 2011b). This knowledge is also helpful for understanding the responses of crops to changing water conditions due to climate change and human activities.

Plant access to available water sources depends on the root distribution along the soil profile. Although excavating plant root systems is time intensive and cost prohibitive, this method has been traditionally and widely used to study plant water uptake patterns in various ecosystems (Dahlman and Kucera, 1965; Jackson et al., 1996). However, Dawson and Pate (1996) and Thorburn and Ehleringer (1995) concluded that the amount and spatial distribution of fine and coarse roots do not accurately reflect the primary water sources utilized by the roots in different soil layers.

Recent studies involving plant water use indicate that measuring the natural abundances of the hydrogen and oxygen stable isotopes in plant stem water and in potential water sources is a powerful and nondestructive method for determining the sources of water used by different plant species (Ehleringer and Dawson, 1992; Nie et al., 2012). The application of this technique has yielded unexpected results regarding the water use strategies of plants in many situations (e.g. Dawson and Ehleringer, 1991; Brooks et al., 2010). These results indicate that the functions of root systems in soils are not fully understood (Gardner, 1991; Brunel et al., 1995; Midwood et al., 1998). For example, the roles of mobile soil water (MSW, the fraction of soil water with high mobility that can easily be replaced by infiltrating rainwater, e.g., the soil water that can be extracted under 80 kPa of suction) and immobile

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Abbreviations: BSW, Bulk soil water; MSW, Mobile soil water; ImSW, Immobile soil water; IR, Isotopic ratio; SPAC, Soil-plant-atmosphere continuum; LMWL, Local meteoric water line; V-SMOW, Vienna-Standard Mean Ocean Water; GMWL, Globe Meteoric Water Line.

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soil water (ImSW, the fraction of soil water with little mobility that is tightly bound to the soil particles) in plant water use strategies remain controversial (Brooks et al., 2010). In addition, a lack of knowledge regarding the root distribution in the soil profile often limits accurate identification of the plant water source when using isotope methods. For example, Bariac et al. (1994) observed that the root density in the soil and the isotopic profile of the soil water were considerably heterogeneous with depth, thus the isotopic data were insufficient for accurately identifying the plant water source.

For annual plants, such as maize, roots gradually grow downwards to a maximum depth, which determines the depth of the accessible water sources in the soil profile. The, direct inference method which is according to the intersection of the isotopic values of plant stem water and soil water to identify the plant's main water source was widely used in plant water sources studies (Brunel et al., 1995). However, the isotopic profiles of soil water can be curved in shape, particularly in shallow soils (Zhao et al., 2013a). For example, the occurrence of two or more intersections of plant water and soil water isotopic values may obscure the identifying the primary water source used by the plant. Consequently, using stable isotope analysis combined with an excavation method which determining plant root depth and biomass throughout the soil profile could be useful for accurately identifying the primary water sources of crops during different growing seasons.

Maize is one of the most important crops grown in the hilly area of southwest China, which is dominated by purple soils. Purple soils have a small available water capacity of 0.06–0.11 $cm^3 \cdot cm^{-3}$ (Wang, 2013), and 73% of the sloping farmland in this region has a soil thickness of 20–60 cm. Soil <60 cm significantly decreased maize yield in this shallow Entisol (Zhu et al., 2009). Cakir (2004) also found that short-duration water deficits during the rapid vegetative growth period caused 28–32% loss of maize yield in such Entisol. This was explained by that the shallow soil layer limits water storage and root penetration (Zhao et al., 2013b). Furthermore, seasonal droughts that decrease crop yields frequently occur in this area. Understanding the water uptake patterns of maize in such shallow soils is important for agricultural water management and hydrological balance in agricultural landscapes. However, the water uptake dynamics of maize in such shallow agricultural soil systems remain unclear.

δD and $\delta^{18}O$ analysis with excavation methods were used to assess the proportions of water uptake by maize from different soil horizons on sloping farmland at a hilly area in southwest China with purple soils. The objectives of this study were to (1) compare the isotopic signatures of the rainwater, bulk soil water (BSW), MSW, and maize stem water in the area to infer the relationships among potential water sources and maize stem water; and (2) determine the water source for maize and the probabilities of the contributions from soil water in different depths to the maize water in purple soils using single-source direct inference and an alternative multiple-source mass-balance approach.

2. Materials and methods

2.1. Study area

This study was conducted at the Yanting Agro-ecological Experimental Purple Soil Station of the Chinese Academy of Sciences, which is located in a hilly area of southwest China dominated by purple soils (31°16′ N and 105°28′ E) (Fig. 1a). This region is characterized by a moderate subtropical monsoon climate, with an annual mean temperature of 17.3 °C and a mean annual precipitation of 826 mm (from 1981 to 2006). From 1981 to 2006, 65.5% of the annual precipitation occurred during the summer. The experimental soil is classified as an Entisol according to Food and Agriculture Organization (FAO) Taxonomy (Gong, 1999; Wang, 2013; Zhao et al., 2013a). The bulk density, porosity, particle size distribution and organic matter content are shown in Table 1 under crop conditions after one month of tillage.

2.2. Sampling and measurements

Field experiments were conducted in a sloping farmland plot that measures approximately 50 m in length and 30 m in width at the experimental station and has a shallow soil profile (average thickness is 40 cm). An overhead view of the study plot is shown in Fig. 1c. The distance of the slope toe to the downslope position of the sloping farmland was approximately 20 m. The crest of the slope was on the upslope position of the sloping farmland. Maize (*Zea mays* L.) was sown on May 23, 2013, at a density of four plants per square meter and was harvested on September 12, 2013. The sampling campaigns were conducted on rainless days or 2–3 days after heavy rainfall. The first internodes of each maize stem were collected at 8 a.m. and stored in glass bottles for plant water sampling. The sampling dates were June 6 (one-leaf stage), July 2 (five-leaf stage), July 27 (elongation stage), August 6 (tasseling stage) and August 29 (grain mature stage) in 2013. Three maize stems were sampled from the upslope, midslope and downslope areas, respectively.

Soil samples were obtained near the stem sampling locations (<1 m apart) using a hand-operated auger at depths of 0–5, 5–10, 10–20, 20–30 and 30–40 cm. At each slope position, suction lysimeters (Soilmoisture Equipment Corp., CA, USA) with a diameter of 48 mm were installed at 2.5, 7.5, 15, 25 and 35 cm. Soil water samples were obtained from the lysimeters at a pressure of −80 kPa after 8 h of equilibrium. The soil water and maize stem samples were collected simultaneously. During the maize growing season, each rainfall event was sampled using a glass funnel (20 cm diameter) that was connected to a high-density polyethylene bottle. A table tennis ball was placed in the funnel to reduce evaporation. In addition, water was collected from the pools in the study catchment to build the local meteoric evaporative line (LMEL). Next, 25 pools were sampled on July 10, 2013. For isotope analysis, the soil, maize stem, and lysimeter soil water samples were placed in airtight glass vials and immediately sealed with airtight caps and parafilm to prevent evaporation. The samples were stored in a refrigerator at 4 °C until analysis. To excavate the maize roots, a pit of one square meter was dug to a depth of 40 cm (bedrock depth) in the field. Maize roots were collected on the same day as the plant stem samples using a depth interval of 10 cm and dried at 75 °C for 48 h until a constant weight was achieved.

The soil water potential was measured using tensiometers (Type T4e, UMS-GmbH, Munich, Germany). Four tensiometers were installed at the middle of each layer at the upslope, midslope and downslope positions along the 0–40 cm soil profiles to represent the soil water potentials at depths of 0–15, 15–25, 25–35 and 35–40 cm, respectively. No data were recorded at depths of 25–35 and 35–40 cm on the downslope during the one-leaf stage because of equipment failure.

The BSW (bulk soil water, total soil water including mobile and immobile soil water) and maize stem water were extracted using a cryogenic vacuum distillation method (Ehleringer and Osmond, 1989). δD and $\delta^{18}O$ analysis were conducted using an L2120-i analyzer (Picarro, USA). The isotope ratios ($^2H/^1H$ and $^{18}O/^{16}O$) are expressed per-mille (‰) for δD and $\delta^{18}O$ and are defined relative to the Vienna-Standard Mean Ocean Water (V-SMOW) (Eq. 1). The analytical precision for each sample was 0.2‰ for $\delta^{18}O$ and 0.5‰ for δD, which were defined as follows:

$$\delta D \text{ or } \delta^{18}O(‰) = (R_{SAMPLE}/R_{V\text{-}SMOW} - 1) \times 10^3 \tag{1}$$

where R_{SAMPLE} and $R_{V\text{-}SMOW}$ are the D/H or $^{18}O/^{16}O$ ratios of the sample and the V-SMOW, respectively.

2.3. Analysis method

First, the hydrogen isotopes were directly compared between the soil water profile and the maize stem water. The depth at which the soil water and stem water isotopic values were similar indicated the