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Stable isotope evidences for identifying crop water uptake in a typical winter wheat–summer maize rotation field in the North China Plain

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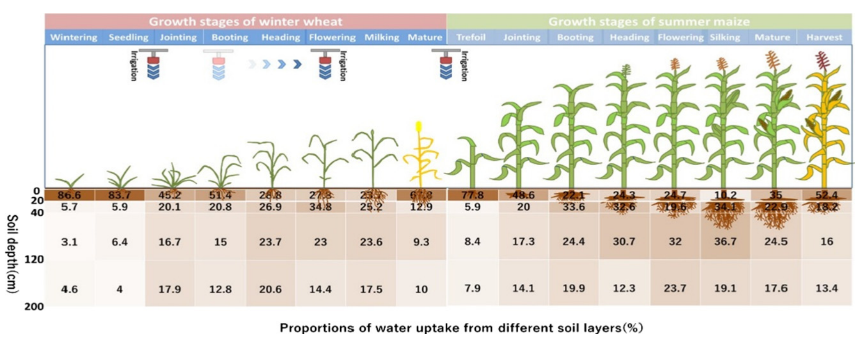
HIGHLIGHTS

- A full crop water uptake diagram was obtained for winter wheat and summer maize.
- Stable isotope and hierarchical cluster analysis were used to classify soil layers.
- Dry root weight density negatively corresponded to wheat's water uptake.
- Soil water content positively corresponded to both wheat and maize's water uptake.
- Irrigation should be suspended from the booting to flowering stages of wheat.

GRAPHICAL ABSTRACT



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ABSTRACT

Better managing agricultural water resources, which are increasingly stressed by climate change and anthropogenic activities, is difficult, particularly because of variations in water uptake patterns associated with crop type and growth stage. Thus, the stable isotopes $\delta^{18}O$ and $\delta^{2}H$ were employed to investigate the water uptake patterns of a summer maize (*Zea mays* L.) and winter wheat (*Triticum aestivum* L.) rotation system in the North China Plain. Based on the soil water content, soil layers were divided into four groups (0–20 cm, 20–40 cm, 40–120 cm, and 120–200 cm) using a hierarchical cluster analysis. The main soil layer of water uptake for summer maize was from 0–20 cm at the trefoil (77.8%) and jointing (48.6%) stages to 20–40 cm at the booting (33.6%) and heading (32.6%) stages, became 40–120 cm at the silking (32.0%) and milking (36.7%) stages, and then returned to 0–20 cm at the mature (35.0%) and harvest (52.4%) stages. Winter wheat most absorbed water from the 0–20 cm soil water at the wintering (86.6%), seedling (83.7%), jointing (45.2%), booting (51.4%), heading (28.8%), and mature (67.8%) stages, but it was 20–40 cm at the flowering (34.8%) and milking (25.2%) stages. The dry root weight density was positively correlated with the contributions of the water uptake for winter wheat. However, no similar correlation was found in summer maize. Regression analysis indicated that the soil volumetric water content (SVWC) was negatively correlated with the contribution of the water uptake (CWU) for summer maize ($CWU = -0.91 \times SVWC + 57.75$) and winter wheat ($CWU = -2.03 \times SVWC + 92.73$). These different responses to water uptake contributions suggested that a traditional irrigation event should be postponed from the booting to flowering stage of winter wheat. This study provides insights into crop water uptake and agricultural water management.

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1. Introduction

Agriculture, commonly a large water-consumption sector, is now facing increasingly greater challenges because of the water scarcity caused by irrational anthropogenic activities and climate change (Wang et al., 2014; Zipper et al., 2015). This is affecting many regions around the world, such as Southern and Eastern Africa, the Middle East, North-West India, South-West America, and Northern China (Rijsberman, 2006). Thus, several studies have been conducted to reduce field evapotranspiration, to improve agricultural water use efficiency, and to develop water-saving technologies. However, the physiological characteristics of crop water uptake remain largely unclear, especially the variation over crop growth stages. Thus, a better understanding of the sources and magnitudes of crop water uptake can greatly help in making optimal reasonable irrigation schemes for better agricultural water management.

As a major grain producing area, the North China Plain (NCP) produces >50% of the wheat yields and ~40% of the maize yields in China (Mo et al., 2016). Correspondingly, a winter wheat–summer maize rotation is the main cropping system in the NCP (Fang et al., 2010). However, these two crops have distinct water uptake patterns (Ma and Song, 2016; Wang et al., 2010; Zhang et al., 2011) because of their unique traits, including their phenological resources utilizations and root systems. Traditional methods used to determine crops water uptake are based on phenological traits or rooting systems (Draye et al., 2010; Fang et al., 2010; Guan et al., 2015; Qiu et al., 2008). However, they have the disadvantages of not identifying the water source and lacking a quantified estimation of each water source, temporally and spatially (Ehleringer and Dawson, 1992). Instead, a stable isotopes (δ^{18}O and δ^{2}H) method can be employed to reveal water uptake patterns with the apparent advantages of being non-destructive and accurately tracing water movement (Ma and Song, 2016; Paces and Wurster, 2014).

Uneven precipitation distribution over the summer maize and winter wheat seasons in the NCP makes crop water uptake patterns highly temporal heterogeneity (Chesson et al., 2004; Moreno-Gutierrez et al., 2012). To identify the water source and water uptake layers, soil layer classification is the primary issue need to be addressed. Currently, there are four main ways to address classifying the water source. Firstly, some studies provided no clear explanations for soil layers classification, such as those of Wang et al. (2010), Zhang et al. (2011), Moreno-Gutierrez et al. (2012), David et al. (2013), Meissner et al. (2014), Wu et al. (2016), and Evaristo et al. (2016). Secondly, others (Ma and Song, 2016) classify soil layers based on the differences in the isotopic composition of soil water. In this case, soil was roughly sorted into shallow, middle, and deep soil layers that were respectively characterized by significant isotopic depletion, light isotopic depletion, and relatively isotopic stability. However, the isotopic compositions reflecting the soil layers characteristic were abstracted from other studies instead of real value in the study. In spite of applying local isotopic compositions of soil layers for soil classification, this also lacks of a statistical analysis of the isotopic composition as in Dai et al. (2015), Song et al. (2016), and Wu et al. (2014). Thirdly, others considered that the root distribution could be used to classify soil layers (Ma and Song, 2016). However, this requires determining the root density in each soil layer prior to the study, which is costly and time- and labor-intensive, especially for plants having long roots in the desert (Dai et al., 2015; Wu et al., 2014). As a matter of fact, soil water content is considered as an environmental factor and resource supply that affects crops. It is easy to be measured and could be a good index for soil classification (Ma and Song, 2016). However, there are few reports on this especially based on statistical analysis.

Although increasing attention has been paid to plant water uptake using stable isotopes in different ecosystems, such as forests (David et al., 2013; Evaristo et al., 2016; Li et al., 2007; Meissner et al., 2014; Moreno-Gutierrez et al., 2012; Song et al., 2016; Yang et al., 2015), croplands (Ma and Song, 2016; Wang et al., 2010; Wu et al., 2016; Zhang et al., 2011), and deserts (Dai et al., 2015; Wu et al., 2014), this issue is far from being fully understood. In a cropland ecosystem, former studies emphasized only one type of crop (Ma and Song, 2016; Zhang et al., 2011). For studies that investigated several plants, the main focus was on co-existing plants spatially competing or cooperating for water resources (Meissner et al., 2014; Moreno-Gutierrez et al., 2012; Wu et al., 2014; Yang et al., 2015). However, studies on winter wheat and summer maize's use of water resources when planted sequentially in a crop rotation are lacking. Furthermore, crop water uptake varies with growth stages; however, previous studies mainly focused on a few growth stages, which may neglect accurate water-sensitive or water-extensive consumption growth stage. For example, Wang et al. (2010) and Zhang et al. (2011) indicated that the shifting water uptake layer lies in the flowering and full ripe stages for summer maize and in the milking and heading stages for winter wheat, but neglected the intervening growth stages. This relatively large temporal scale could not result in precise recommendations for irrigation practices.

To remedy this deficiency, stable isotopes δ^{18}O and δ^{2}H were applied to quantify water uptake in a summer maize and winter wheat rotation field in the NCP. The specific objectives of this study are: 1) to identify the main water uptake layers of summer maize and winter wheat at full growth stages; 2) to calculate the contributions of water uptake from each water source at different growth stages for summer maize and winter wheat; 3) to explore the relationships between crop water uptake and relevant factors; and 4) to optimize current irrigation management practices.

2. Materials and methods

2.1. Site description

This study was conducted at the Yucheng Comprehensive Experiment Station (YCES), Chinese Academy of Sciences, which is located in Dezhou (36°56′N, 116°40′E, 23 m a.s.l.), NCP. It has a warm temperate semi-humid and semi-arid climate. The annual mean air temperature is 13.3 °C and the annual precipitation is 559.8 mm according to the long-term observation in YCES (1980–2015). Precipitation is distributed unevenly, with 70% of the annual precipitation falling between June and September. The annual sunshine is 2640 h. The soil type is Aquents with high salinity (Soil Survey Staff, 1999). A winter wheat–summer maize rotational cropping system predominates at this study site.

2.2. Sample collection

The sampling campaigns were carried out in the Sino-Japanese Joint Field at the YCES from June 2015 to July 2016. The field was rotationally planted with wheat (*Triticum aestivum* L., Jimai-22) and maize (*Zea mays* L., HY-1). Wheat and maize were sown in mid-October and mid-June, respectively, and harvested in early June and early October, respectively. Fertilizer was generally applied at the following three times: 1) before wheat sowing, 2) in March, and 3) between the jointing and flare opening stage of maize. Also, irrigation sessions were carried out at the following three times: 1) in March, 2) between the booting and flowering stages of wheat, and 3) before maize sowing.

Crop xylem, soil, and root samples at different depths were collected at eight growth stages from winter wheat (wintering, seedling, jointing, booting, heading, flowering, milking, and mature stages) and summer maize (trefoil, jointing, booting, heading, silking, milking, mature, and harvest stages). Also, soil at different depths after a precipitation event was collected. Xylem was cut from crops and the epidermis was gently removed using tweezers. Accordingly, roots at 0–5, 5–10, 10–20, 20–40, 40–60, 60–80, and 80–100 cm soil layers were extracted using a soil auger (10-cm diameter) with a sharpened edge. Adjacent soil samples were collected at layers of 0–5, 5–10, 10–20, 20–40, 40–60, 60–80, 80–100, 100–120, 120–150, and 150–200 cm using a 10-cm diameter auger. Then, the xylem and soil samples were quickly placed into 20-