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RESEARCH ARTICLE

Estimating distribution of water uptake with depth of winter wheat by hydrogen and oxygen stable isotopes under different irrigation depths

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Abstract

Crop root system plays an important role in the water cycle of the soil-plant-atmosphere continuum. In this study, combined isotope techniques, root length density and root cell activity analysis were used to investigate the root water uptake mechanisms of winter wheat (*Triticum aestivum* L.) under different irrigation depths in the North China Plain. Both direct inference approach and multisource linear mixing model were applied to estimate the distribution of water uptake with depth in six growing stages. Results showed that winter wheat under land surface irrigation treatment (T_s) mainly absorbed water from 10–20 cm soil layers in the wintering and green stages (66.9 and 72.0%, respectively); 0–20 cm (57.0%) in the jointing stage; 0–40 (15.3%) and 80–180 cm (58.1%) in the heading stage; 60–80 (13.2%) and 180–220 cm (35.5%) in the filling stage; and 0–40 (46.8%) and 80–100 cm (31.0%) in the ripening stage. Winter wheat under whole soil layers irrigation treatment (T_w) absorbed more water from deep soil layer than T_s in heading, filling and ripening stages. Moreover, root cell activity and root length density of winter wheat under T_w were significantly greater than that of T_s in the three stages. We concluded that distribution of water uptake with depth was affected by the availability of water sources, the root length density and root cell activity. Implementation of the whole soil layers irrigation method can affect root system distribution and thereby increase water use from deeper soil and enhance water use efficiency.

Keywords: hydrogen and oxygen stable isotopes, multisource linear mixing model, winter wheat, distribution of water uptake with depth

1. Introduction

The North China Plain accounts for approximately 18.3% of the domestic farm lands, and winter wheat (*Triticum aestivum* L.) production in this area represents approximately 50% of the total production in North China Plain (Liu *et al*. 2015; Yang *et al*. 2015). Considering that root system plays an important role not only in plant water absorption but also in the water cycle of the soil-plant-atmosphere continuum (SPAC), studies on the winter wheat root system are of great importance. In recent years, a number of studies have focused on the spatial distribution of winter wheat root, and some researchers attempted to reveal the root water uptake mechanisms of winter wheat through excavation (Yang *et al*. 2010; Nosalewicz and Lipiec 2014; Guan *et al*.

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2015). However, the morphological structure of roots cannot always represent the root water absorption ability (Flanagan *et al*. 1992; Thorburn and Walker 1994). Thus, root water uptake patterns cannot be indicated solely by relying on root distribution (Thorburn and Ehleringer 1995; Midwood *et al*. 1998a; Asbjornsen *et al*. 2007).

The stable isotope technique is increasingly applied in water cycle research in SPAC (Dawson *et al*. 2002; Sulzman *et al*. 2007). Isotopic fractionation occurs in physical transport processes, so the isotopic signatures of various water pools tend to be different, which contribute to the use of hydrogen and oxygen isotopes as natural tracers to describe the water pathway in natural environment (Dawson and Simonin 2011; Schwendenmann *et al*. 2015). The determination of plant water source is a widespread application of hydrogen and oxygen stable isotopes technique (Dawson *et al*. 2002). This application is based on the fact that the isotope signature of xylem water is a mixture of different water sources accessible for the plant (Dawson and Ehleringer 1991; Ehleringer *et al*. 1991). Except for some specific salt-tolerant plants, no isotopic fractionation of hydrogen and oxygen stable isotopes occur during root absorption and transportation (Dawson and Ehleringer 1991; Lin *et al*. 1993; Dawson *et al*. 2002). Therefore, based on isotope mass balance theory, the proportional contributions of probable water sources can be estimated by comparing the hydrogen and oxygen stable isotopes signatures between plant xylem and water sources (Brunel *et al*. 1997; Phillips and Gregg 2003).

In recent decades, many studies have employed the stable isotope technique to research water sources of plants. For example, in the riparian ecosystem, riparian tress absorb limited stream water; instead, trees prefer to use the more stable water source, such as groundwater (Dawson and Ehleringer 1991; Smith *et al*. 1991; Busch *et al*. 1992; Thorburn and Walker 1994; Dawson and Pate 1996; Snyder and Williams 2000). Dawson and Pate (1996) stated this phenomenon is attributed to the fact that stream water is unstable because of flood and seasonal precipitation changes, whereas ground water is relatively stable. To survive in drought environment, riparian trees use more groundwater than stream water. Studies on coastal plants demonstrated that the water sources of these plants can be sea water, fresh water, or a combination of both (Sternberg and Swart 1987; Sternberg *et al*. 1991; Lin and Sternberg 1994). Lin and Sternberg (1994) noted that hydrogen isotope fractionation may occur during root absorption for some salt-tolerant plants. In arid and semi-arid areas, the contribution of different water sources varies with seasonal changes (Ehleringer *et al*. 1991; Flanagan *et al*. 1992; Yoder *et al*. 1998; Chimner and Cooper 2004). Although several studies have investigated the water source of plants, such as trees and grasses, few have focused on field crops (Wang *et al*. 2010; Zhang C *et al*. 2011; Zhang Y *et al*. 2011). When it comes to winter wheat, Zhang *et al*. (2011b) employed the stable isotope technique to research on the water contribution of soil water within 100 cm depth, and they found that the main water uptake depths are 0–40 cm soil layers in all growing stages. However, winter wheat root can extend to a depth of 200 cm since the jointing stage. Soil layers below 100 cm were supposed to be taken into account when analyzing the mechanisms of winter wheat root water uptake. Moreover, no research has combined root length density, root cell activity study and water source partition based on the stable isotope technique to provide integrated analyses of root water uptake of winter wheat.

In this study, we combined the water source partition study based on the hydrogen and oxygen stable isotopes technique, root length distribution and root cell activity study to explore the water uptake rules of winter wheat. Precipitation and irrigation water need be transformed to soil water before being absorbed by roots. During infiltration, evaporation will occur and lead to isotope fractionation. Direct use of precipitation and irrigation water as water sources will enrich the "heavier" isotope and lead to inaccurate results of water source partition (Dawson 1998; Ingraham and Mark 2000). Therefore, the water sources in this study were the soil water in different soil layers. We used direct inference approach and IsoSource software based on the multisource mass balance method to confirm the proportional water contribution of different soil layers. The results of this study not only contribute to the understanding of water cycle mechanisms of SPAC, but also enhance the water-saving irrigation management of winter wheat.

2. Results

2.1. Isotopic composition of water sample

Craig (1961) first discovered a linear relationship between $\delta^{18}O$ and δD of precipitation, which is referred to as the global meteoric water line (GMWL): $\delta D=8\times\delta^{18}O+10$. The interception of the equations is also called D-excess. The local meteoric water line (LMWL) of this study is: $\delta D=7.78\times\delta^{18}O+2.38$ (R=0.949) (Fig. 1). The lower slope and D-excess were caused by humidity changes and secondary evaporation of raindrop (Araguás-Araguás *et al*. 1998; Peng *et al*. 2010). The linear fitting of the soil water isotope composition is $\delta D=6.09\times\delta^{18}O-14.30$ (R=0.927). Meanwhile, the slope and interception difference was caused by evaporation effect and the fact that soil water was the mixture of precipitation and irrigation water.