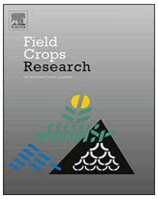
Field Crops Research 215 (2018) 113–121

Contents lists available at ScienceDirect

Field Crops Research

journal homepage: www.elsevier.com/locate/fcr



Determining root water uptake of two alpine crops in a rainfed cropland in the Qinghai Lake watershed: First assessment using stable isotopes analysis

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ARTICLE INFO

Keywords:
Stable isotopes
Root activity
Soil water availability
MixSIAR model
Alpine agriculture

ABSTRACT

Knowledge of crop root water uptake (RWU) is critical for understanding agricultural water management. However, the mechanisms underlying the RWU of alpine crops in rainfed cropland remain poorly understood. This study investigated seasonal variations in water uptake of oilseed rape (*Brassica napus* L.) and highland barley (*Hordeum vulgare* L.) coupled with dual stable isotope tracers at different growth stages. The method of direct inference showed that the soil depth layer from which water was predominantly taken up by roots was 0–30 cm. More specifically, oilseed rape and highland barley exhibited different RWU patterns: oilseed rape had the high flexible performance and could revert to deep soil layers (30–60 cm) as the main water source according to soil water availability due to short-term droughts at the peak growth stage. In contrast, water uptake by highland barley was primarily derived from both shallow and middle soil layers ($<$ 30 cm) throughout all growth stages. These findings indicated that the appropriate irrigation wetting depth should be above 30 cm for the different growth stages.

1. Introduction

Accurate estimation of water availability is crucial to evaluating root water uptake (RWU) of plants, especially in environments where water availability is highly variable and difficult to predict. Water availability partly determines plants' ability to extract water and their response to soil moisture dynamics. However, the magnitude of the available water constraint on crop yield is controlled by the balance between the water source exploited by roots and atmospheric demand throughout the growing season (Dardanelli et al., 1997; Smith, 2000; Yang et al., 2015). There is a need for detailed information on crop RWU in response to changing water conditions in rainfed cropland.

Stable hydrogen (δ^2H) and oxygen (δ^{18}O) isotope tracing techniques have provided a powerful method for identifying different plant RWU patterns (Asbjornsen et al., 2008; Schwendenmann et al., 2015; Zhang et al., 2017). The application of this method has provided unexpected results on the water use strategies of plants in various habitats (Dawson and Pate, 1996; Nippert and Knapp, 2007; Grossiord et al., 2017). These findings suggest that plant root functions are not completely understood (Williams and Ehleringer, 2000; Wu et al., 2014). For instance, root presence *per se* does not indicate root activity in soil layers, greatly determining plant RWU (Donovan and Ehleringer, 1994; Williams and Ehleringer, 2000; Wu et al., 2016a). Especially for some plants, the RWU depth distribution changes with the growth stage or with seasonal soil water availability. Wu et al. (2016a) reported that the introduced shrub *Hippophae rhamnoides* mainly extracted water from shallow soil layers in the early growing season but shifted its water source to deep soil when shallow soil water became less available in water-limited ecosystems. Thus, investigations of plant RWU across seasons are necessary to improve understanding of root activity and plant–water relations in these ecosystems.

Numerous studies have focused on water use patterns of plants such as trees and grasses in semi-arid regions, showing that some plants could adjust their flexibility of water uptake depth to acclimate to the change in soil water availability (Nippert and Knapp, 2007; Dai et al., 2015; Sun et al., 2015). Recently, several limited studies have applied isotopic tracers to identify positions of crop water uptake (Sekiya and Yano, 2002, 2004; Wang et al., 2010; Zhang et al., 2011a; Yang et al., 2015; Ma and Song, 2016; Rothfuss and Javaux, 2017). For example, Ma and Song (2016) quantified the contributions of soil water to summer maize (*Zea mays* L.) during growing stages using a MixSIAR Bayesian mixing model. Wang et al. (2010) assessed the water uptake

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http://dx.doi.org/10.1016/j.fcr.2017.10.011
Received 12 June 2017; Received in revised form 10 October 2017; Accepted 12 October 2017

patterns of summer maize and cotton in Shanxi Province, China, where the depth of water accessed by maize and cotton varied seasonally. Yang et al. (2015) observed that irrigated maize extracted water preferentially from the shallow soil (0–10 cm) and thus improved the efficiency of irrigation water use in the Heihe River Basin, China. Despite these efforts, most studies employing the isotopic tracer technique have focused on irrigated field crops. To our knowledge, no water isotope study has investigated the RWU of alpine crops in the rainfed cropland.

Oilseed rape (*Brassica napus* L.) and highland barley (*Hordeum vulgare* L.) are the most important oil and grain feed alpine crops around Qinghai Lake and are extensively grown. Under rainfed conditions, their average seed yields are about 1245 kg/ha in the watershed, clearly lower than in the eastern agricultural regions of Qinghai Province due to the harsh climatic conditions (Chen et al., 2008). The whole watershed receives average annual precipitation of approximately 303 mm during the short growing period of May–September (Ma, 2011). However, transpiration by crops consumes almost all precipitation and RWU leads to low soil moisture (approximately 26.7–30.2% in 0–60 cm of cropland soils; Ma, 2011). Diepenbrock (2000) showed that short-duration water deficits during the rapid vegetative growth period resulted in loss of oilseed rape yield. This can be explained by limited water storage in shallow soil layers (Wang et al., 2010; Zhang et al., 2011b; Zhao et al., 2016). Furthermore, seasonal drought frequently occurs in this cropland (Sun et al., 2007) and reduces crop yields (Diepenbrock, 2000; Jing and Dong, 2004). Hence, understanding water uptake patterns of the two crops is crucial for determining irrigation schedules and agricultural water management in the region.

Interestingly, other studies have shown that highly competitive crops (e.g., maize and pigeon pea) can induce downward displacement of part of the root system (Sekiya and Yano, 2002; Wang et al., 2010), decreasing competition in the upper soil layers and increasing dependence on the complementary water sources from deep soil layers. However, this root function remains unclear for oilseed rape and barley. According to the root distributions of both species, we hypothesized that (1) oilseed rape could flexibly shift its water sources between shallow and deep soil water in response to soil moisture availability, and (2) barley primarily depended on shallow soil water. To test our hypotheses, the isotopic compositions of crop xylem water and potential soil water sources were collected in rainfed cropland during two consecutive growing seasons. This study aimed to (1) quantify the contribution of potential water sources to oilseed rape and barley RWU and (2) compare the water uptake patterns for these crops at different growth stages.

2. Materials and methods

2.1. Study area

The study site (37°21′N, 100°14′E, 3217 m) is in the lower reaches of the Shaliu River in the north of Qinghai Lake (Fig. 1). This region belongs to a semi-arid, cold and alpine climate zone dominated by the East Asian monsoon during the growing season. The mean annual temperature and precipitation amount are approximately 0.1 °C and 400 mm, respectively. The seasonal distribution of precipitation is uneven, with approximately 65% during the growing season of May-–September, primarily characterized by small precipitation events of less than 5 mm (Wu et al., 2016b). The soil in the study area mainly consists of chestnut soil according to Food and Agriculture Organization (FAO) Taxonomy (Goog, 1999), with an average soil thickness of 60–100 cm. The bulk density, particle size and organic matter content are given in Table 1.

The staple crops in this region are mainly oilseed rape and grain crops (e.g., barley and oats [*Avena sativa* L.]). Oilseed rape and barley are cultivated in the Qinghai Lake watershed and oilseed rape is an important cash crop. The two crops are sown in early June and harvested in late September. The growth stage of oilseed rape differs from barley. For example, the growth stages of oilseed rape were seedling (25 June 2013, 29 June 2014), stem elongation (18 July 2013, 15 July 2014), flowering (29 July 2013, 24 July 2014), pod-filling (9 August 2013, 1 August 2014) and mature (24 August 2013, 20 August 2014). In contrast, the six growth stages for barley were seedling (25 June 2013, 29 June 2014), jointing (18 July 2013, 15 July 2014), booting (29 July 2013, 24 July 2014), heading (9 August 2013, 1 August 2014), grain filling (24 August 2013, 20 August 2014) and mature (9 September 2013, 5 September 2014). The sampling dates during two consecutive growing seasons are given in Table 2. Irrigation only occurred before the crops were sown in the study site, using water sourced from the Shaliu River; no irrigation was conducted during the growth stages. The cropland area is approximately 3.22×10^4 ha in this region. Interestingly, the annual yield and planting area of oilseed rape have obviously increased since 1993 compared with grain crops (Fig. 2), which may be due to its rising price and the boom of scenic tourism in the region.

2.2. Experiment design and sampling

Two years of seasonal field experiments were conducted in a cropland field plot approximately 1 km from the research station of Sanjiaocheng Sheep Breeding Farm (Fig. 1). The whole cropland has a shallow soil profile (average thickness of 60 cm). Three plots (5 m × 5 m) were positioned in the oilseed rape and barley fields, respectively. Sampling for oilseed rape and barley was conducted on rainless days or several days after rainfall in their specific growing stages. In addition, meteorological data were obtained from an automatic weather station located in nearby grassland (Fig. 1b).

During each growth stage of oilseed rape and barley, soil water at depths of 10, 20, 30, 40 and 60 cm and crop xylem water were collected for stable isotope analysis. For crop xylem water sampling, Barnard et al. (2006) reported that water isotopic composition of the root crown best reflected that of the plant water sources. Thus, crop root crowns were collected for isotopic analysis. The crop height and rooting depth were measured in each field plot at each growth stage in 2014 using a 1-m ruler. Concurrently with the crop water sampling, all soil water samples were collected using a hand auger and sealed in glass with Parafilm for isotopic analysis. In addition, other parts of the collected soil were used for gravimetric soil water content (SWC, %) analysis, which was determined by oven drying at 105 °C for 24 h. To prevent the effect of evaporation on isotopic contents, all soil and plant samples were stored in a refrigerator (–4 °C) until water was extracted using cryogenic vacuum distillation.

Samples of precipitation events were collected using a rainwater collector, composed of a 10-cm-diameter funnel connected to a brown glass bottle. Each sample was removed when a precipitation event stopped. A total of 117 precipitation samples were collected and sealed in clean polyethylene bottles with Parafilm during the growing season in 2013 and 2014. All precipitation samples were stored in a refrigerator (–4 °C) until isotopic analysis.

2.3. Isotopic analysis

Water in the soil and crop stems was extracted by a cryogenic vacuum distillation system (West et al., 2006). The hydrogen and oxygen isotopic compositions (δ^2H and δ^{18}O) in all samples including precipitation, soil water and crop water were analyzed by the off-axis integrated cavity output spectroscopy method (Model DLT-100, Los Gatos Research, San Jose, CA, USA). Measurement of hydrogen and oxygen isotopic compositions of water were calibrated and normalized to internal laboratory water standards previously calibrated relative to the Vienna Standard Mean Ocean Water (VSMOW). The measurement accuracy was consistently ± 1.2‰ for δ^2H and ± 0.3‰ for δ^{18}O.