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Coupling evapotranspiration partitioning with root water uptake to identify the water consumption characteristics of winter wheat: A case study in the North China Plain

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ABSTRACT

Quantifying the contribution of transpiration (T) to evapotranspiration (ET) and determining the main water source for crops at different growth stages are two essential steps for developing water-saving agricultural strategies. In this study, an improved S–W (SWH) model and the MixSIAR model were used for ET partitioning and water source prediction in an irrigated cropland in the North China Plain. Our results indicated that the partition results of SWH model are well consistent with those from micro-lysimeter measurements. T/ET ranged from 13.4% to 87.0% with a mean value of 71.4%, which always exceeded 80% during the peak growing season. Based on δD and $\delta^{18}O$ in xylem and soil water, we found that winter wheat derived approximately 78.1 ± 8.9% of its water from the 0–50 cm soil stratum. At the sub-daily time scale, root water uptake from 20 to 50 cm depth mainly occurred during the late afternoon (12:00–18:00 LST). Soil water evaporation was approximately 107.8 mm over the season, 55.8% of which was lost during the filling stage. These results are expected to have implications for the sustainability of irrigated agriculture in this area.

1. Introduction

Agriculture is the biggest consumer of water resources worldwide, with over 70% of the total ground and surface water being utilized for irrigation (FAO, 2013). More than 90% of water inputs will either evaporate (E) or be used by plants for transpiration (T), together referred to as evapotranspiration (ET) (Rana and Katerji, 2000). Water conservation requires an effective and rational control of E, which was not directly contributing to crop productivity (Jensen et al., 2014; Wen et al., 2016). An accurate partitioning of ET is the first challenge for scientific research (Schlesinger and Jasechko, 2014; Good et al., 2015). Quantifying root water uptake is another key issue in the optimization of the wetting depth of irrigation water (Zhang et al., 2011; Yang et al., 2015a). Therefore, both ET partitioning and water source prediction, i.e. the primary soil layers that provide water for root water uptake, are necessary for arranging irrigation schedules.

In spite of the ET partitioning efforts over the decades, determining the components of the partitioned fluxes remains very challenging within both modeling and measuring approaches (Kool et al., 2014; Sutanto et al., 2014). The first analytical model that incorporated E and T to partition ET was proposed by Shuttleworth and Wallace (1985) (i.e., S–W model). The S–W model is a modification of the Penman-Monteith model, which is another commonly used model for ET partitioning. Canopy stomatal resistance is one of the key factors affecting the performance of S–W model, however, it is usually regarded as a constant owing to its difficulty of estimation (Iritz et al., 1999; Gash and Shuttleworth, 2007). Recently, the Ball-Berry stomatal conductance model was incorporated into the S–W model (i.e., SWH model), and successfully applied in forest and grassland ecosystems (Hu et al., 2009, 2013). Measurement approaches for ET partitioning include the micro-lysimeter, sap-flow and stable isotopes, etc (Liu et al., 2002; Wang and Yakir, 2000; Jasechko et al., 2013).

Stable isotopes of hydrogen and oxygen (δD and $\delta^{18}O$) have received great attention for prediction of water sources in forest, grassland, and cropland ecosystems (Eggemeyer et al., 2009; Liu et al., 2010; Yang et al., 2015b). The underlying assumption is that no isotopic fractionation occurs during water uptake of plant root (Ehleringer and Dawson, 1992). Previous studies determined the plant water sources mainly by the direct comparison method (Sekiya and Yano, 2002) and IsoSource mixing model (Phillips et al., 2005). MixSIR is one of the Bayesian mixed models that explicitly takes into account the uncertainties (i.e., the uncertainties in isotope signatures and multiple

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sources) in plant water source predictions (Moore and Semmens, 2008). A new Bayesian model of MixSIAR has been recently proposed, which includes the features of source fitting (both for raw data and means + SDs), error structure options (residual, combined source, or both), and option to include individual eff ;ects, etc. (Stock and Semmens, 2013). However, these statistical models provide only a range of feasible contribution of each water source instead of a unique solution.

North China Plain (NCP) accounts for as much as one-fifth of the total grain yield of China, thus, playing an important role in ensuring the food security in China. In recent decades, the groundwater resources in NCP have been extensively exploited for irrigation, owing to the rapid expansion of winter wheat-growing areas (Li et al., 2010). Previous studies have focused mainly on the effects of irrigation schedule on the crop yield and water use efficiency of winter wheat (Sun et al., 2006; Zhang et al., 2011). The objectives of this study are to quantify the T-to-ET ratio using the SWH model, and investigate the water uptake patterns of winter wheat based on the isotopic labeling. We hypothesized that (i) the SWH model, which was calibrated by the measured ET, would be as reliable as the micro-lysimeter measurements (ii) winter wheat utilize water primarily from shallow depths due to the frequent irrigation.

2. Materials and methods

2.1. Overview

This study combined modeling and micrometeorological approaches as a way to provide an integrated analysis of ET partitioning. Specifically, performance of the SWH model was evaluated using the micro-lysimeter measurements. In addition, using isotopic labels, plant water sources for winter wheat were assessed over one growing season. The water fluxes for various pools were calculated according to water conservation principles. The proportional contributions of each water source to winter wheat were calculated based on the MixSIAR model. Data were collected during the 2008 growing season (April 1–June 18).

2.2. Site and data

The experiments were conducted at the Luancheng Agro-ecosystem Experimental Station (37°50′ N, 114°40′ E, 50 m), located in the North China Plain (Wen et al., 2012; Xiao et al., 2012). Northerly winds prevail from September to February, while southeasterly winds reign from March to August. The cultivar of winter wheat (*Triticum aestivum* L.) was “Kenong 199″, which was planted in November of 2007, and harvested on 18 June [days of year (DOY) = 170] in 2008. The cultivation area was approximately 16 ha. At this site, three irrigations, of 60–80 mm each, are commonly applied from the reviving until the jointing and heading stages (Li et al., 2010; Zhang et al., 2011). The field capacity is approximately 0.36% for the 0–160 cm layers (Sun et al., 2006). The soil has a mean wilting point of 0.14%. The dominant soil type is silt loam, with a density of 1.40–1.57 g cm^{-3}. Soil texture is divided into the particle grades of 2.0-0.05 mm (22.2 ± 0.06%), 0.05-0.002 mm (55.8 ± 0.05%), and < 0.002 mm (22.0 ± 0.09%).

2.3. Eddy covariance and micrometeorological measurements

An Eddy Covariance (EC) system (Li-7500, Licor Inc., Lincoln, NE, USA; CSAT-3, Campbell Scientific Inc., Logan, UT, USA; CR5000, Campbell Scientific Inc., Logan, UT, USA) was installed at a height of 3.5 m from the ground. The distances between EC system and the edges of the field were more than 800 m. The fetch for the predominant wind direction was greater than 200 m (Xiao et al., 2012). The 30-min mean CO_2/H_2O fluxes were calculated and stored by the data logger. In brief, the double coordination rotation was performed to remove the effect of instrument tilt (or irregularity) on air flows. The Webb-Pearman-Leuning (WPL) correction was applied to correct the effect of air density fluctuations on CO_2 and water vapor fluxes. Missing ET values (~33.5%) were interpolated based on the linear regression between available evapotranspiration and net radiation data of the adjacent 48 h.

Micrometeorological measurements consisted a suite of sensors for providing 30-min average micrometeorological data for net radiation (CNR-1, Kipp and Zonen Inc., Delft, Netherlands), air temperature (HMP45C, Vaisala Inc., Helsinki, Finland), soil water content (CS615-L, Campbell ScientificInc., Logan, UT, USA) and precipitation (52203, RM Young Inc., Traverse City, MI, USA), etc. A leaf conveyor belt (Li-3050 A, Licor Inc., Lincoln, NE, USA) and a leaf area meter (Li-3000, Licor Inc., Lincoln, NE, USA) were used to measure the leaf areas about every 10 days. During the entire study period (DOY 92-170), the maximum plant canopy height was 0.75 m, and the maximum leaf area index (LAI) was 4.52 m^2 m^{-2}.

Six homemade micro-lysimeters (ML) were pushed into the soil to measure the daily E (Wen et al., 2016). The MLs were 10 cm in diameter and 15 cm in height, which were made out of polyvinyl chloride (PVC) tubes. They were sealed at the bottom, placed back into the soil, and weighed after a period of 24 h (17:00–18:00 LST). The raw data of MLs were converted to day timescale (0:00–24:00 LST) according to net radiation, which had the best correlation with the weight changes of MLs. To ensure a soil moisture content similar to the outside conditions, the undisturbed soil in the ML was retrieved every 3–4 days. If there was rainfall or irrigation, they were changed immediately.

2.4. Isotopic measurements of plant and soil water

Xylem and soil samples were collected from four plots (5 m × 6 m) that were distributed diagonally (Xiao et al., 2012). Most of the samples were collected at midday (12:00-14:00 LST) every 3–4 days. Around the sampled crops, soil samples from 0 to 50 cm were collected at three depths to approximately represent the soil strata of 0–5, 5–20, and 20–50 cm. Soil from 0 to 160 cm depth (at 0–1, 1–2, 2–3, 3–5, 5–10, 10–20, 20–30, 30–50, 50–80, 80–120, and 120–180 cm) were also sampled weekly at midday. During the intensive field campaigns (DOY 135–137 and 142–144), plant and soil samples were collected at 06:00, 12:00, and 18:00 LST. Rainwater of 17 rainfall events were sampled using a self-made rain collector that comprised a polyethylene bottle and a funnel (with a ping-pang ball for preventing evaporation). All the samples were sealed with parafilm and frozen (−15 °C to −20 °C) immediately after collection.

A vacuum line was used to cryogenically extract the water in plant and soil samples. The liquid samples were analyzed using an isotope ratio infrared spectroscopy (IRIS) system (DLT-100, Los Gatos Research, Mountain View, CA, USA). δD and δ^{18}O of xylem water were corrected for the organic contaminations following the procedure of Xiao et al. (2012). The average correction for xylem water was 1.8 ± 0.7‰ for δD and 0.79 ± 0.51‰ for δ^{18}O.

2.5. Models

2.5.1. The improved S–W model

The S–W model (Shuttleworth and Wallace, 1985; Gash and Shuttleworth, 2007) describes the two separate flows of water vapor arising from plant transpiration (T) and soil water evaporation (E). By incorporating the Ball-Berry stomatal conductance model, Hu et al. (2009, 2013) developed a new S–W model (i.e., SWH model) to estimate ET and its components. The key challenge of the modeling approaches was to estimate the five resistances from the soil surface to the reference height. In this study, the resistance of the soil surface (r_{ss}, s m^{-1}) was estimated as (Lin and Sun, 1983):

$$r_{ss} = b_1\left(\frac{\theta_s}{\theta}\right)^{b_2} + b_3 \tag{1}$$