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Evapotranspiration and its partitioning in an irrigated winter wheat field: A combined isotopic and micrometeorologic approach

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SUMMARY

Groundwater overdraft threatens the future of irrigated agriculture in the North China Plain. Because irrigated winter wheat is the dominant user of extracted groundwater, improved understanding of water cycling through the soil–plant–atmosphere continuum during wheat cultivation in the North China Plain is necessary for improving the sustainable utilization of limited water resources and promoting food security. In this paper, a combination of micrometeorological and stable isotope techniques was used to investigate evapotranspiration and soil water dynamics in a typical winter wheat agro-ecosystem (Luancheng Agro-ecosystem Experiment Station, Hebei Province). Stable isotope mixing models were used with eddy covariance evapotranspiration estimates and micro-lysimeter evaporation measurements to partition evapotranspiration and determine temporal variability of root water uptake depths. Results suggest that evaporation during the winter wheat irrigation season can reach up to 30% of the total water consumption (almost two typical irrigations). The main depths of root water uptake were 0–40 cm. Therefore, it is suggested that the planned irrigation wetting depth can be reduced at least to 40 cm, rather than the traditional 100 cm, as a means of water conservation. Widespread implementation of these practices could amount to a significant water savings for the North China Plain.

1. Introduction

Food production in the North China Plain (NCP) is critical to domestic food security in China (Deng et al., 2006; Foster et al., 2004). Groundwater irrigation has been central to increasing agricultural productivity in the NCP over the past four decades. However, current rates of groundwater withdrawal exceed natural groundwater recharge rates (Kendy et al., 2004), and regional water tables have fallen rapidly as a result. This situation also affects other aspects of the regional hydrological cycle including baseflow to rivers, which adversely affects stream flow and riparian ecosystems (Piao et al., 2010; Deng et al., 2002). Groundwater resource sustainability for food production will depend upon balancing groundwater consumption with replenishment.

Irrigation accounts for the majority of groundwater use in the North China Plain. Therefore, development of more water-efficient agricultural practices is a key component of strategies for curbing groundwater depletion in the region (Tong et al., 2009; Zhang et al., 2004b). Winter wheat is one of the most extensively grown crops in the NCP. It has high demand for irrigation water because of scarce precipitation during its growing period from March to June (Shen et al., 2002). The Soil–Plant–Atmosphere Continuum (SPAC) of the NCP's winter wheat agroecosystem has been extensively studied over the past three decades (Liu, 1997; Liu and Sun, 1999; Philip, 1966), with much attention paid to water transfers among precipitation, soil water, ground water, plant-stem water, and atmospheric water vapor. The NCP receives an average annual precipitation of approximately 120 mm during the winter wheat growing season (Sun et al., 2010). Without irrigation, transpiration by winter wheat consumes nearly all precipitation and root water uptake results in consistently low soil moisture contents (approximately 20% in typical NCP soils between 0 and 40 cm. Zhang et al., 2004a). Soil moisture plays important roles in the rainfed situation by: (1) providing initial soil moisture storage to supplement rainfall following a fallow period and (2) modulating irregular timing of precipitation events (Cooper et al., 1987; Li et al., 2005; Rosegrant et al., 2002; Smith, 2000). Under rainfed conditions, typical winter wheat yield was about 3600 kg/ha (Sun et al., 2010). Yields increase with increasing water application to approximately 5500 kg/ha for the typical irrigation application of 180 mm/yr under current agricultural practices for winter wheat (Sun et al., 2010). It is estimated that this level of yields requires approximately 460 mm/yr of evapotranspiration (Sun et al., 2006). Based on estimates suggesting

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that evaporation was approximately 30% of the total evapotranspiration (Liu et al., 2002), about 140 mm of applied irrigation water is lost to evaporation. These are inefficiencies in the system which, if reduced, will significantly reduce groundwater depletion and large groundwater savings can be achieved (Wang et al., 2001). Reductions in shallow soil water evaporation in agricultural areas may represent the greatest current opportunity for groundwater conservation in the NCP because irrigated agricultural land use and urban water demands are likely to remain high in coming years.

Detailed knowledge of water cycling within the winter wheat agro-ecosystem is required in order to inform cultivation practices that can achieve better water use efficiency. In particular, refining strategies to increase the ratio of transpiration to other soil water balance sink terms (evaporation and deep drainage) necessitates (1) evapotranspiration partitioning and (2) characterization of the vertical and temporal variability of transpiration within the root zone. Stable isotopes can be used to partition ecosystem ET based on the differences in isotopic compositions ($\delta^{18}O$ and $\delta^{2}H$) of water fluxes from stem water and soil water (Yakir and Sternberg, 2000). Numerous previous studies have successfully measured the partitioning between transpiration and evaporation using the isotope method (e.g. Brunel et al., 1997; Yepez et al., 2003). However, this information has not been coupled with a characterization of root water uptake depths over the growing season. Vertical variability of root water uptake has traditionally been studied by root system excavation (Dahlman and Kucera, 1965; Zhang et al., 2004a). One limitation of this approach is that the excavation can significantly affect the growing environment. In contrast, the isotope tracer technique is minimally intrusive and therefore more suitable for long-term research. The primary objective of this study was to determine the temporal variability of evapotranspiration structure and major layers of soil water for root uptake throughout the winter wheat growing season in the NCP. This study utilizes a hybrid micrometeorological/isotopic approach which is applied in the NCP for the first time. The study advances knowledge of soil water cycling in the NCP by quantifying depth-specific soil water contributions to evaporation and transpiration throughout the growing season.

2. Materials and methods

2.1. Overview

This study combined micrometeorological and isotopic methods as a way to provide integrated analyses of root water uptake and the ET partitioning. Stable isotopes are excellent tracers of soil water cycling because of the isotopic fractionation imparted by evaporation. Isotope compositions of soil water, groundwater, plant-stem water, precipitation, and atmospheric water vapor were analyzed over one growing season. Evapotranspiration was independently estimated with eddy covariance and a micro-lysimeter system (MLS, Shen et al., 2002). The study was undertaken concurrently on two adjacent plots: one receiving a fully irrigation as the well-watered treatment and one control plot under rainfed conditions for comparison. Both treatments were used in the soil water contribution analysis while only the irrigated treatment was used for ET partitioning. Data were collected during the 2009 growing season (1 March 2009–4 June 2009; basic climate conditions are summarized in Table 1).

2.2. Site description

The experiments were conducted at Luancheng Experimental Station of Agro-ecosystem (LESA, 37°53′N, 114°41′E, altitude 50.1 m), which is located in the middle of the piedmont plain of the Taihang Mountains, Shijiazhuang, Hebei Province. It is a high-yield agricultural area of about 13,500 kg ha^{-1} (Shen et al., 2002), with winter wheat–summer corn rotation each year. It has a semi-arid monsoonal climate. The mean annual precipitation is 480 mm, most of which occurs from July to September. It is often droughty in the winter wheat season from March to June, when the mean actual ET of about 340 mm (March–June) greatly exceeds the mean precipitation of about 60 mm (Table 2). The mean annual temperature at the station is 12 °C. Generally, 3–4 irrigation applications of 60–80 mm each are carried out in a typical growing season. Water table depth has increased dramatically from 11 m in 1975 to 35 m in 2009 with a drawdown rate of approximately 0.7 m per year (Fig. 1). The water table recovers slightly after precipitation events, but declines dramatically at the onset of pumping for growing season irrigation. Soil in the experimental plots is a fertile loam (Table 3, Sun et al., 2007). Soil moisture field capacity is approximately 34% above 100 cm (Sun et al., 2006).

2.3. Field methods

Rainfed and well-watered experimental plots were 5 m × 10 m, constructed with walls that are 24.5 cm thick and extend 1.5 m beneath the surface to avoid soil water recharge (Zhang et al., 2004b). The rainfed treatment was never irrigated and the well-watered plot was irrigated to maintain no less than 85% of field capacity. Both plot experiments have been operating for approximately 15 years. Three irrigation applications totaling 230 mm were applied in April and May 2009. Soil volumetric moisture content was measured by a neutron probe (IH-II, Institute of Hydrology, Wallingford, UK) at 10 cm intervals from a depth of 0–180 cm. Depth to the water table was measured by water level logger

Table 1
The monthly mean climate and total precipitation at LESA in 2009.

Month	January	February	March	April	May	June	July	August	September	October	November	December	Annual
P (mm)	0.0	5.7	8.4	8.0	41.3	54	75.3	245.7	77.3	0	41.3	0.3	557.3
T (°C)	−3.3	1.4	7.5	17.0	20.2	26.4	26.9	25.0	19.7	15.8	0.3	−1.6	12.9
RH (%)	78.1	71.8	76.2	92.6	89.3	70.4	95.6	112.2	104.5	80.2	108.6	86.9	88.9
WS_{10m} (m/s)	2.0	2.4	2.8	2.9	3.0	3.0	2.7	1.6	1.8	2.2	2.1	2.7	2.4

Table 2
The water requirement during growing stages of winter wheat at LESA in 2009.

Growing stages	Reviving	Jointing	Heading	Filling	Maturity
Date	DOY60–DOY90	DOY91–DOY105	DOY106–DOY125	DOY126–DOY150	DOY151–DOY155
ET (mm)	54.5	67	57.1	114	45
Precipitation (mm)	5.1	3.3	8	40.6	0.7
Shortage (mm)	49.4	63.7	49.1	73.4	44.3
Irrigation (mm)	0	80	68	82	0