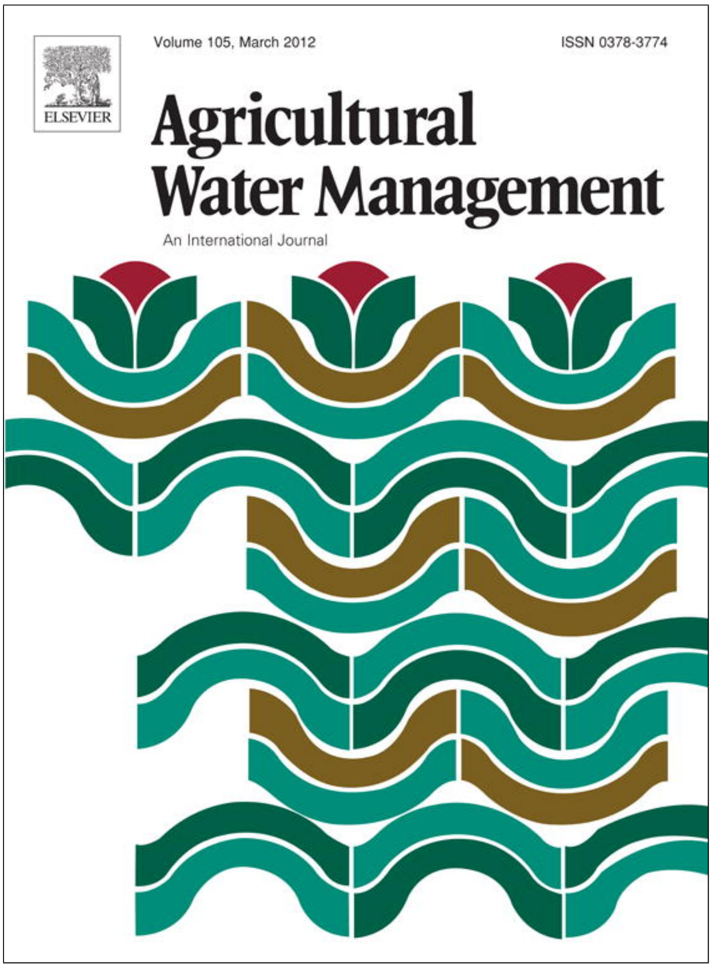
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Determination of evaporation, transpiration and deep percolation of summer corn and winter wheat after irrigation

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ABSTRACT

The flux of evaporation, transpiration and deep percolation play an important role in agricultural water management. In this study, oxygen-18 was used to determine the three fluxes in the summer corn and winter wheat field under existing irrigation pattern in Shanxi Province, China. Precipitation, irrigation water, soil water, groundwater and stem water were sampled for oxygen-18 analyses, and supported by hydrological observations. By the method of soil water balance and isotope mass balance, combined with eddy correlation method, the following results are reached. After the irrigation on August 11th, 2008 for summer corn (flowering stage, 90 mm, flood irrigation), transpiration of corn accounts for 71.3% of total evapotranspiration, and the irrigation water use efficiency is 38.0%. And after the irrigation on March 15th, 2009 for winter wheat (re-green stage, 110 mm, sprinkler irrigation), transpiration of winter wheat accounts for 61.7% of evapotranspiration, and the irrigation water use efficiency is 42.3%. Compared to flood irrigation, the deep percolation loss of irrigation water under sprinkler irrigation is lower, especially in the first day after irrigation. Overall, the existing irrigation efficiency is low in study area, and measures should be taken to reduce the deep percolation after irrigation.

1. Introduction

Water scarcity is a big problem in China, and the average amount of water per person in China (2300–2400 m^3/year) is only about one quarter of the world average. Especially in North China, where large population exists, agriculture, industry and municipalities demand more water than available. Agricultural irrigation accounts for 65% of China's annual water use, which totals 560 billion cubic meters (Li and Peng, 2009). In many areas, groundwater is drawn for irrigation at rates higher than recharge rates leading to water table decline. Meanwhile, the efficiency of irrigation water use is low. China produces less than 1 kg of grain with 1 m^3 of water, only about half compared to developed countries (Shan and Zhang, 2006). Improving the efficiency of irrigation water is vital for sustainable development of water resources and environment protection in China.

The fate of irrigation water in agricultural fields can be summarized as: direct evaporation from the soil surface; transpiration of crops; deep percolation below the crop root zone. The amount of water transpired is important, since in essence it is the only water which passes through the crop associated with growth and yield. Thus, improving water use efficiency becomes an optimization problem where transpiration should be maximized and evaporation as well as deep percolation should be minimized.

Some methods have been developed to quantify evaporation, transpiration and deep percolation in field studies, such as by using large-scale weighing lysimeter (Liu et al., 2002; Lopez-Urrea et al., 2009), sap flow method (Jara et al., 1998; Trambouze et al., 1998), micro-meteorological methods (Williams et al., 2004; Wolf et al., 2008; Yunusa et al., 2004), remote sensing (Immerzeel et al., 2008; Stehman and Milliken, 2007) and hydrological models (Droogers, 2000; Mo et al., 2005; Tourula and Heikinheimo, 1998). Usually, some methods are combined together to calculate evaporation, transpiration and deep percolation. Those methods are usually costly and time-consuming, and calculations are often complicated by different measuring scales, especially during periods following precipitation or irrigation events when soil water content and canopy conductance are changing rapidly (Huxman et al., 2004).

Stable isotopes of water, ^{2}H and ^{18}O have been widely used in studies of water movement in the soil-vegetation-atmosphere continuum. Evaporation, or the loss of water from soil, results in the fractionation of soil water isotopes (Zimmermann et al., 1967). Consequently, soil evaporation alters both the soil water content and soil water isotopic composition. In contrast, transpiration, which is the loss of water through stomata and cuticle, does not fractionate soil water isotopes at steady state (Bariac et al., 1991). So

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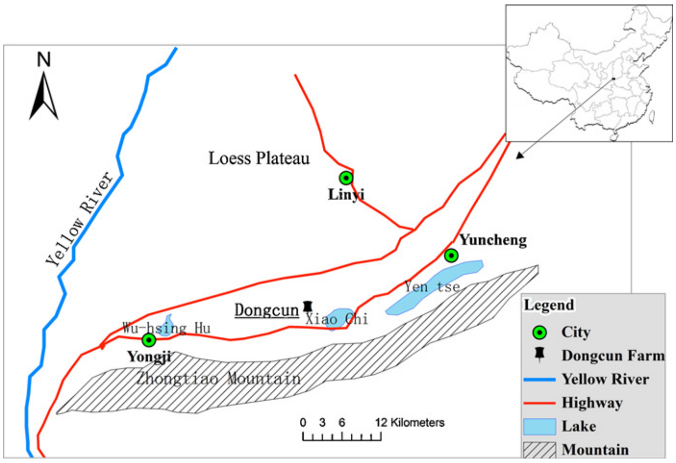

Fig. 1. Location of Dongcun farm.

evaporation from soil and transpiration from plants both decrease the soil water content, but have different effect on isotopic composition of residual soil water. Those theories have been used to determine the rate of evaporation and transpiration (Hsieh et al., 1998; Robertson and Gazis, 2006; Wenninger et al., 2010).

In this study, soil water balance and isotopic mass balance are used to determine the evaporation, transpiration and deep percolation in summer corn and winter wheat field after existing irrigation pattern in Dongcun farmland, Shanxi Province, China, and evaluate its current irrigation water use efficiency.

2. Materials and methods

2.1. Study area

The study area (Fig. 1), Dongcun farm (110°44′35.8″E, 34°55′43.2″N) is located in the southern part of the Shanxi Province at 300–500 m above mean sea level. The basin is bordered in the north and east by the Loess Plateau and in the south by the Zhongtiao Mountain. The western boundary is defined by the Yellow River flowing southward. It is a traditional agricultural area due to its rich soil and advantaged climatic conditions. Dongcun has a farmland of about 270 km^2 and the main crops are winter wheat–summer corn and cotton. The region belongs to the warm temperate zone with a continental monsoon climate, which is dry and cold in winter, rainy and hot in summer. Precipitation from June to September accounts for more than 70% of annual precipitation, and the average annual precipitation is 590 mm, with large interannual variability from minimum 288 mm to maximum 919 mm. The average annual temperature is 13.1 °C, and the maximum is observed in July with extreme value of 42.4 °C and minimum in January of −18.7 °C (1972–2009). The depth to water table is shallow, which is about 1.2–1.4 m, and the shallow groundwater has high salinity, so the irrigation water is drawn from deep groundwater (about 200 m below surface). Soil texture in this area is silt loam, which is mainly comprised of sand and silt with a small proportion of clay.

2.2. Measurements and sampling

In this study soil water dynamics were monitored and precipitation, irrigation water, soil water, groundwater and stem water was sampled for oxygen stable isotopes analysis.

The soil water content was calculated by the soil water potential and the soil water retention curve. The soil water potential was observed by tensiometer in summer corn and winter wheat experimental fields. Each field had one profile, and the depths of observation are 10, 20, 30, 40, 50, 70, 90, 120 and 150 cm. The data were recorded manually at 8:00 in the morning every day with precision of 1 mm Hg. The soil water retention curve was fitted by soil water potential and soil water volumetric content. The soil water potential was measured by tensiometer, while the soil water volumetric content was calculated by soil water weight content (drying method) and bulk density (core cutter method).

Meteorological conditions, including precipitation, temperature, moisture, wind speed and direction, and net solar radiation were monitored by the automatic weather station (CAMS-III, data recorded per 15 min). The evapotranspiration of crop field was determined by the eddy covariance method based on the observations of LI-7500 open path CO_2/H_2O analyzer.

The precipitation samples were collected in 500 ml vials through a 200 mm diameter funnel, in which a ping-pong ball was placed to avoid evaporation. The rainfall samples were gathered into two 50 ml polyethylene air-tight vials after a rain event. The collection of the groundwater was carried out by 4 groundwater observation wells in the experimental fields and the depth of water table was measured every day.

The soil water was sampled by suction lysimeters which were constructed out of Teflon pipe and a porous ceramic cup, and installed at the bottom of 5 cm diameter holes excavated with a hand-operated bucket auger, backfilled with the excavated material. Soil water was collected by applying a vacuum of about −0.8 MPa to the suction lysimeter. Using this method, 10–500 ml of water samples can be taken with little effect on oxygen-18 (Swistock et al., 1989). The soil water was sampled at the same depths as the tensiometers.

The corresponding crop stems were collected when soil water was sampled. Each sample had 3–5 stems which were far from the leaves. The crop stem samples were put in a 4 ml glass bottle, sealed with parafilm to prevent evaporation, and refrigerated immediately.

Cryogenic vacuum distillation method (Ehleringer and Osmond, 1989) was used to extract crop stem water in the lab. For the cryogenic vacuum distillation, two glass tubes were attached to a vacuum pump. The sample was placed in one tube and frozen by submerging the tube in liquid nitrogen, and then both tubes were evacuated by vacuum pump to create a closed U-shape configuration. After that, the tube containing sample material was heated to 90 °C, while the other was cooled by liquid nitrogen to collect the evaporated water. An extraction time of 60–90 min was required depending on the water content of the samples. The efficiency of water extracting by this equipment was tested by Wang et al. (2010).

The water samples were analyzed at the Environmental Isotope Laboratory of Institute of Geographic Sciences and Natural Resources Research, Chinese Academy of Sciences. $\delta^{18}O$ was measured using a Finnigan MAT253 mass spectrometer. Results were expressed as parts per thousand deviations from the Vienna Standard Mean Ocean Water (V-SMOW). A precision of ±0.1‰ (2 STDV) was obtained for $\delta^{18}O$ in standard water samples.

2.3. Analysis method

Based on the soil water balance and isotope mass balance, the following equations can be obtained for the soil column:

$$m_f - m_i = m_p - m_e - m_t - m_z \quad (1)$$

$$\delta_f m_f + \delta_e m_e + \delta_t m_t + \delta_z m_z = \delta_i m_i + \delta_p m_p \quad (2)$$

$$m_{ET} = m_e + m_t \quad (3)$$

where m represents soil water content; δ represents the value of $\delta^{18}O$; f,i represents final and initial state of soil water; p represents precipitation or irrigation; e represents evaporation of soil water; t

represents transpiration of crops (equals the root water uptake of crops); z represents the deep percolation of soil water.

The soil water content (m_f, m_i) is calculated by the soil water potential and the soil water retention curve; the evapotranspiration (m_{ET}: $m_e + m_t$) is determined by eddy covariance method. Based on Eq. (1), the deep percolation (m_z) can be calculated. $\delta^{18}O$ of precipitation, irrigation (δ_p), soil water (δ_f, δ_i) and transpiration (δ_t, replaced by the $\delta^{18}O$ of stem water of crops) are measured based on field sampling. $\delta^{18}O$ of evaporation (δ_e) is calculated based on the fractionation factor $\alpha_{\text{liquid–vapor}} = (\delta_l + 1000)/(\delta_v + 1000)$, assuming that the evaporated water (δ_v: δ_e in Eq. (2)) is in isotopic equilibrium with soil water (δ_l: δ_i in Eq. (2)). As α is variable with temperature, mean air temperature during the study time is used to determine α (Clark and Fritz, 1997), which is approximately 25 °C (α = 1.0093) and 15 °C (α = 1.0102) for summer corn and winter wheat field, respectively. $\delta^{18}O$ of deep percolation of soil water (δ_z) is replaced by the water-content-weighted mean $\delta^{18}O$ of soil water at depths below Zero Flux plane (ZFP). Based on the Eqs. (2) and (3), evaporation and transpiration after irrigation can be calculated.

These equations are also based on the following assumptions: lateral variation of soil properties and lateral soil water movement are both minimal; the $\delta^{18}O$ of root uptake water of crops equals to that of stem water, that is to say, the transport time of water up the crops is minimal; the interception loss of sprinkler irrigation is ignored in the calculation for water balance. In this study, the winter wheat is on re-green stage, with a low leaf area index. According to Kang's experiments (Kang et al., 2005), the interception loss will be less than 0.5 mm, which is negligible.

Two irrigation events are chosen to determine the evaporation, transpiration and deep percolation. One is on August 11th, 2008 for summer corn (flowering stage, 90 mm flood irrigation ($\delta^{18}O$ = −9.53‰): irrigation A), and the other is on March 15th, 2009 for winter wheat (re-green stage, 110 mm sprinkler irrigation ($\delta^{18}O$ = −9.66‰): irrigation B). After the irrigation A, there is a 24 mm rainfall ($\delta^{18}O$ = −9.82‰) on August 11th.

In the calculation, the soil water balance and isotope mass balance are considered only within the upper 50 cm of the soil column to determine evaporation of soil water and transpiration of crops, because both of them mainly occur within 50 cm depth (Wang et al., 2010). The deep percolation is defined as the water passes downward out of 0–120 cm soil column, and the soil water balance within 0–120 cm is considered.

3. Results and discussion

3.1. Soil water content and $\delta^{18}O$ profile

Zero Flux plane (ZFP) is defined as a plane, which separates two zones in the soil profile with upward and downward water flow occurring simultaneously (Sadeghi et al., 1984). In this study, ZFP is determined by the total soil water potential, which is composed of soil water matric potential measured by tensiometer and gravity potential whose zero value is set at 150 cm depth below surface. After the irrigation A (Fig. 2), ZFP is at 20 cm depth on the first day, interrupted by the rainfall on the second day, then extends to 30 cm depth on next three days, and stabilizes at 50 cm on the last two days. After the irrigation B, ZFP is not apparent for the first four days (maybe exists between 0 and 10 cm, which has no observations), and extends from 30 to 40 cm in the next three days. ZFP is less developed after irrigation B than irrigation A, maybe due to its sprinkler irrigation mode, leading to relatively slow percolation, which will be discussed below. Overall, ZFP is developed from 0 to 40–50 cm in 7 days after irrigation, which can suggest the evaporation mainly occurs in the soil profile 0–50 cm.

Table 1
Parameters for soil water balance and isotopic mass balance after irrigation A.

Parameter	Date				
	2008/8/13	2008/8/14	2008/8/15	2008/8/16	2008/8/17
m_f (mm)	161.59	154.21	146.65	142.18	137.61
$\delta_f m_f$ (‰)	−939.11	−874.17	−798.99	−754.20	−707.85
m_i (mm)	173.26	161.59	154.21	146.65	142.18
$\delta_i m_i$ (‰)	−1040.16	−939.11	−874.17	−798.99	−754.20
δ_t (‰)	−9.47	−8.73	−9.61	−10.03	−7.65
δ_e (‰)	−16.55	−16.17	−16.63	−16.03	−16.19
$\delta_z m_z$ (‰)	−85.66	−40.29	−32.29	−18.12	−8.03
m_{ET} (mm)	1.33	2.39	3.71	2.28	3.57

After the irrigation, the soil water content (Fig. 3) decreases remarkably for the surface layer (this trend is temporally interrupted by the rainfall on August 12th, 2008 for summer corn). For example, in the 7 days after irrigation, the soil water content at 10 cm depth decreases from 0.35 to 0.25. While for the deep layer (below 50 cm depth), the decrease of soil water content is smaller, due to its little evapotranspiration and the recharge from groundwater by capillary.

The profile of $\delta^{18}O$ (Fig. 4) on the first day after irrigation is analogous, suggesting the water percolates through the whole soil column quickly after irrigation. With time, 5 cm depth is becoming enriched in the $\delta^{18}O$. For irrigation B, the $\delta^{18}O$ at 10–20 cm depth is also becoming enriched, but to a lesser extent; for irrigation A, this trend is interrupted temporarily by the rainfall after irrigation. For deeper layers below 30 cm, no obvious enrichment of $\delta^{18}O$ exists, showing the evaporation of soil water mainly occurs in the 0–30 cm soil column.

3.2. Evaporation and transpiration

Evapotranspiration of crop field determined by the eddy covariance after irrigation is partitioned into evaporation of soil water and transpiration of crops based on soil water balance (Eq. (1)) and isotopic mass balance (Eq. (2)) in 0–50 cm soil column. The parameters used in the equations are shown in Tables 1 and 2.

The results are shown in Fig. 5. After irrigation A, the evapotranspiration ranged from 1.33 to 3.71 mm/day, which is relatively low. This is due to the cloudy weather after irrigation, and the atmospheric humidity is more than 80% on the first two days, and 60–80% in the following days. After irrigation A, the T/ET ratio is 70.1%, 78.4%, 72.2%, 71.9% and 63.9%, respectively in five days, averaging 71.3%; after irrigation B, the evapotranspiration ranged from 2.49 to 4.25 mm/day, and the T/ET ratio is 64.4%, 73.2%, 66.9%, 45.5% and 58.6%, respectively in five days, averaging 61.7%.

Williams et al. (2004) combined eddy covariance, sap flow, and stable isotope techniques to investigate the responses of transpiration and soil evaporation to an irrigation event in an olive orchard in Marrakech, Morocco, and the results show that transpiration accounted for 100% of total ET prior to irrigation, but only 69–36%

Table 2
Parameters for soil water balance and isotopic mass balance after irrigation B.

Parameter	Date				
	2009/3/16	2009/3/17	2009/3/18	2009/3/19	2009/3/20
m_f (mm)	163.09	156.17	152.27	145.40	139.24
$\delta_f m_f$ (‰)	−855.89	−792.01	−752.25	−681.43	−623.20
m_i (mm)	173.09	163.09	156.17	152.27	145.40
$\delta_i m_i$ (‰)	−941.95	−855.89	−792.01	−752.25	−681.43
δ_t (‰)	−10.38	−9.54	−7.93	−8.20	−7.80
δ_e (‰)	−16.81	−16.59	−15.80	−15.25	−15.02
$\delta_z m_z$ (‰)	−55.12	−30.19	−9.75	−18.95	−18.15
m_{ET} (mm)	2.49	2.78	2.53	4.25	3.61

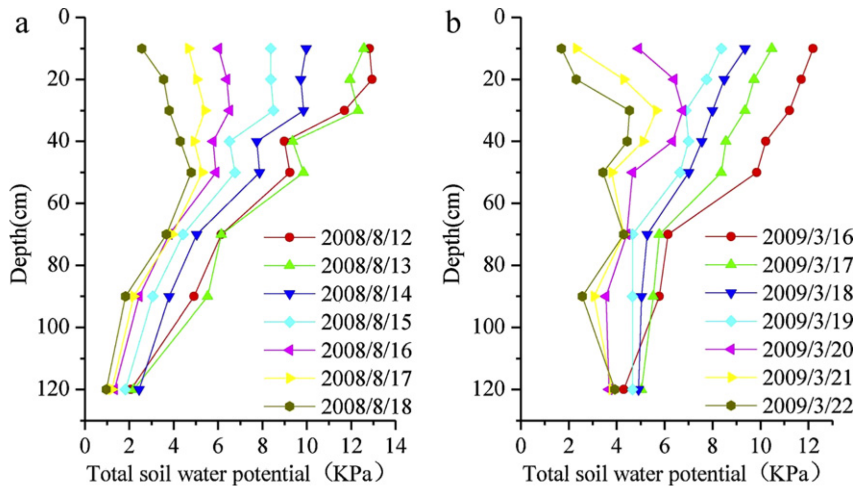

Fig. 2. Profile of total soil water potential after irrigation. (a) Irrigation A for summer corn and (b) irrigation B for winter wheat.

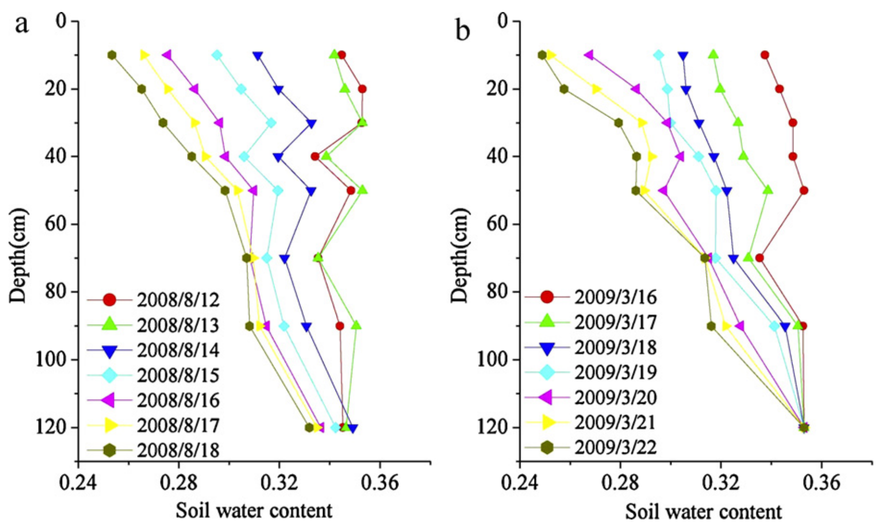

Fig. 3. Profile of soil water content after irrigation. (a) Irrigation A for summer corn and (b) irrigation B for winter wheat.

of ET during peak midday fluxes over the 5-day period following irrigation. Jara et al. (1998) measured the transpiration by sap flow method and evaporation by micro-lysimeters in a corn field after irrigation, and found that transpiration represents 86.4% of daytime ET. Liu et al. (2002) found that transpiration took up 70.3 and 69.7% of the total evapotranspiration for irrigated winter wheat and summer corn field in the growing season, respectively, at Luancheng Station in the North China Plain, based on the measurement of

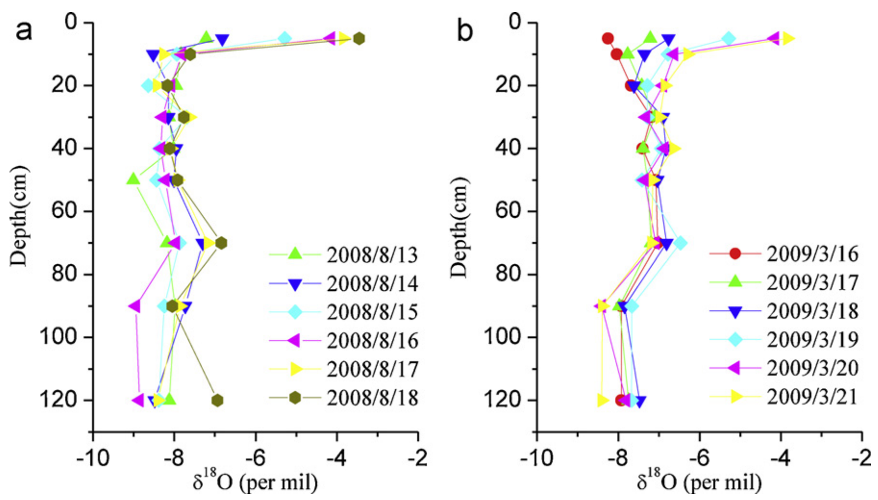

Fig. 4. Profile of $\delta^{18}O$ after irrigation. (a) Irrigation A for summer corn and (b) irrigation B for winter wheat.

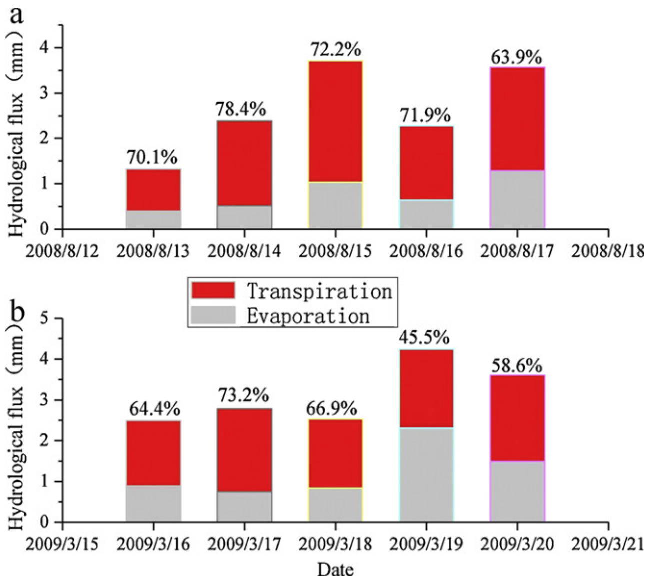

Fig. 5. Evaporation and transpiration calculated after irrigation. Percentage represents the ratio of transpiration of summer corn to evapotranspiration (T/ET). (a) Irrigation on August 11th, 2008 for summer corn and (b) irrigation on March 15th, 2009 for winter wheat.

large-scale weighing lysimeter and two micro-lysimeters. These research conclusions about T/ET in irrigated field are similar to our results in this study, so the method of soil water balance and isotopic mass balance to partition the evaporation and transpiration in study area is credible. However, for the researches not related to irrigation, the partitioning results have some difference. The T/ET ratio is relatively low for plants under semi-arid or arid climate (Brunel et al., 1997; Ferretti et al., 2003), and relatively high under humid climate, which has similar moisture conditions as after irrigation. Hsieh et al. (1998) studied the T/ET in soils along an arid to humid transect in Hawaii by oxygen-18, and the T/ET ratio increased from 14% to 71%.

3.3. Deep percolation and irrigation water use efficiency

The deep percolation in our study is defined as the water passes flowing downwards below 0–120 cm soil column (Fig. 6), and is calculated based on water balance (Eq. (1)).

The deep percolation is up to 21.6 mm on the first day after irrigation A, and decrease quickly in the following days, with 1.75 mm on the seventh day. The trend is similar for irrigation B, but the percolation is much lower on the first day, only 8.8 mm. This could be related to the difference of irrigation patterns, A is flood irrigation and B is sprinkler irrigation.

In this study, we define irrigation water use efficiency (IWUE) as the ratio of transpiration after irrigation to total irrigation water amount. The deep percolation is ignored from the eighth day after irrigation for its negligible amount, and the ratio of E/T from the eighth day is considered as the mean value in the seven days. The rainfall after irrigation A is assumed to be discharged as deep percolation, and this amount is subtracted from total deep percolation. The results of IWUE are shown in Fig. 7.

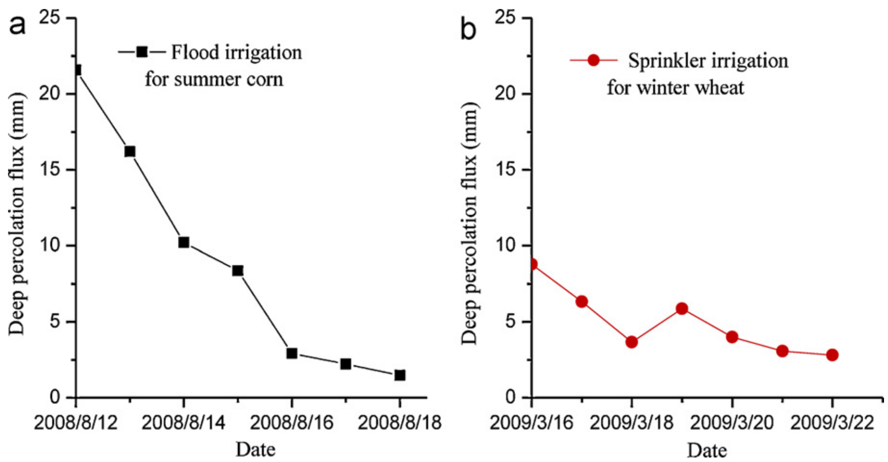

Fig. 6. Deep percolation after irrigation for (a) summer corn and (b) winter wheat.

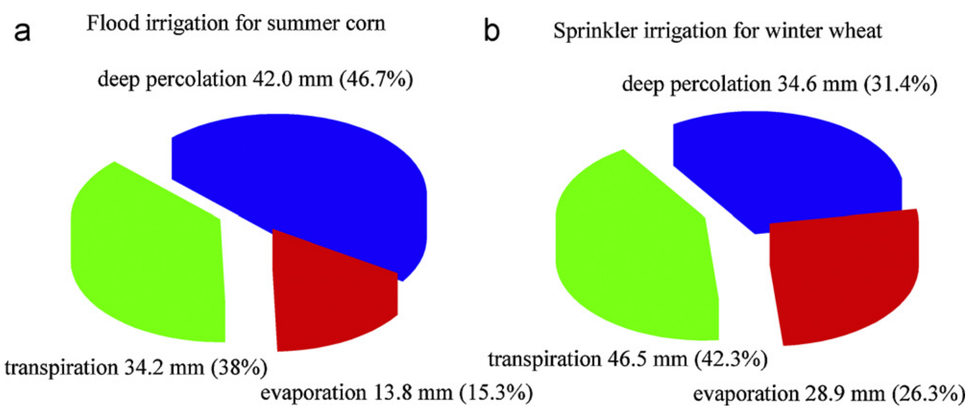

Fig. 7. Consumption of irrigation water and water use efficiency.

The IWUE in this study is 38.0% for irrigation A, and 42.3% for irrigation B. Deep percolation takes up a large proportion, 46.7% and 31.4% respectively for irrigation A and B. Compared to flood irrigation A, the deep percolation loss of irrigation water under sprinkler irrigation B is lower, especially in the first day after irrigation. However, the IWUE of the existing irrigation system in this farmland is relative low, and measures, for example, reducing the irrigation amount, should be taken into account to improve IWUE, especially to reduce the deep percolation.

4. Conclusions

Profiles of soil water content and δ^{18}O value reflect the progress of evapotranspiration and infiltration after irrigation. Both the movement of zero flux plane and enrichment of δ^{18}O suggest evaporation mainly occurs in the soil layer 0–50 cm. By the method of soil water balance and isotope mass balance, combined with eddy correlation method, the T/ET ratio is on average 71.3% after the irrigation on August 11th, 2008 for summer corn (flowering stage, 90 mm, flood irrigation); and after the irrigation on March 15th, 2009 for winter wheat (re-green stage, 110 mm, sprinkler irrigation), the T/ET ratio is on average 61.7%.

The water use efficiency of the existing irrigation system in this farmland is relative low. The water use efficiency in this study is 38.0% after flood irrigation for summer corn, and 42.3% after sprinkler irrigation for winter wheat. The deep percolation takes up a large proportion, up to 46.7% and 31.4% respectively for the two irrigations. Measures should be taken to reduce the deep percolation to improve the water use efficiency.

Our experiments are carried out under the condition of two irrigations, and the results will not be common, but they can give more insight into the consumption of irrigation water and help improve the existing irrigation system in study area.

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