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An isotope method to quantify soil evaporation and evaluate water vapor movement under plastic film mulch

Youjie Wu, Taisheng Du*, Risheng Ding, Yusen Yuan, Sien Li, Ling Tong

Center for Agricultural Water Research in China, China Agricultural University, Beijing 100083, China

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ABSTRACT

Plastic film mulch is a cropping system feature for water saving that is used extensively in arid and semiarid areas. However, research on water flow beneath and through the perforated film mulches is still limited, and the detailed processes of vaporization and transport of evaporation vapor in the soil are not examined thoroughly. Here we used an isotope-based method to quantitatively describe the processes of the soil water and vapor exchange in a maize field under plastic mulch. Micro-lysimeter-based methods and sap flow combined with soil water balance method (E(F-B)) were conducted to compare and verify the results. It shows that heavy oxygen isotope (^{18}O) depleted and enriched alternately along with the processes of condensation and distillation, and enriched again when the second evaporation occurred in condensation water adhered in plastic film. Soil evaporating front was presented in 5–10 cm soil layer, and the exchange motions of water vapor occurred in 0–5 cm soil layer before it diffused to the outside. During the whole maize growing season, about 4.5% of soil water in the 0–20 cm soil layer was evaporated, and 72.6% of the evaporation vapor was condensed and 70.0% of this condensation water was evaporated again. About 2.3% of soil water evaporated through plastic film holes, with the mean evaporation rate of 0.80 mm/d. A good agreement was found between the evaporation determined by our isotope-based method (E(Iso)) and (E(F-B)) method. The evaporation rate was relatively high with the ratio of E to ET around 21.2%, although the areas of the holes only taking up 0.5–5.0% of the whole area of the plastic cover. Therefore, the isotope-based method was robust in estimating evaporation under plastic film mulch. These quantitative analyses will improve our understanding of the mechanism of soil water movement and vapor exchange under plastic mulch and provide accurate estimation of evaporation in field.

1. Introduction

Plastic film mulch has become a globally agricultural practice due to the ability to save water, improve production and increase crop water use efficiency especially in the arid and semi-arid regions (Li et al., 2013; Steinmetz et al., 2016; Xie et al., 2006). As a special surface cover, it evidently influences soil temperature, moisture and surface microclimate, and is often used to protect seedlings and shoots by reducing soil evaporation and maintaining soil temperature and humidity (Han et al., 2015; Wang et al., 2009; Wang et al., 2016; Yang et al., 2012). However, the physical processes between top soil and plastic film mulch such as the vapor exchange and its quantification are remains uncertain. Research on soil water and vapor movement beneath and through the perforated film mulches is still limited. It is a critical and challenging issue to clarify the mechanism of water vapor movement and quantify soil evaporation with plastic film mulch. If the problems above could be solved effectively, the accuracy of field evaporation estimating will be further improved, and it will be very useful for agricultural water management.

Evaporation, as the first step in the hydrologic cycle, plays a crucial role in hydrometeorology system (Cappa, 2003). Although the evaporation rate with plastic film mulch is much lower than that of bare soil, the evaporation process from the soil surface is not negligible, especially in a long term. Conventional methods have been developed to quantify evaporation and its vapor movement in field studies, such as weighing lysimeter measurements (Cavanaugh et al., 2011; Li et al., 2013; Liu et al., 2002; Mitchell et al., 2009; Zhao et al., 2015), micro-meteorological methods (Li et al., 2013; Wolf et al., 2008; Yunusa et al., 2004), remote sensing (Immerzeel et al., 2008; Stehman and Milliken, 2007) and hydrological models (Droogers, 2000; Yang et al., 2012; Zhao et al., 2015).

* Corresponding author.
E-mail addresses: dutaisheng@cau.edu.cn, dts1975@126.com (T. Du).

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Each of these methods suffer from poor spatial representation or time-consuming. Furthermore, high-spatial density measurements are usually limited by instruments, and calculations are often complicated under the plastic film mulch, during which the second evaporation occurred in condensation water adhered in plastic film along with the process of soil water and evaporation vapor exchange, and it has been reported in few studies (Steinmetz et al., 2016).

As the stable isotopes of liquid soil water and water vapor are natural tracers of water movement, they can provide useful information to understand and quantify the vapor exchange (Allison and Hughes, 1983; Braud et al., 2009; Wu et al., 2016a; Yepez et al., 2003). Stable isotopes hydrological analysis approach has become common since it is relatively easy and robust to measure the isotope compositions in water and vapor (Araguás-Araguás et al., 1995; Cappa, 2003; Meißner et al., 2013; Sutanto et al., 2014; Wu et al., 2016a; Yamanaka and Yonetani, 1999). Compared with other methods such as energy balance and modeling, this isotopic technique partially fills the gap in investigation of evaporation by providing information on the water distillation and condensation processes. Soil evaporation alters both the soil water content and isotopic composition, and results in the fractionation of soil water isotopes (Zimmermann et al., 1968). The isotopic fractionation effects determine the isotope values of both evaporating vapor and residual water by discriminating heavier isotopes in the process of water phase changes (Gat et al., 1994; Kim and Lee, 2011). Isotopic compositions of liquid soil water change in response to the fractionation processes of evaporation and condensation (Gat, 1996) and are thus dynamically linked to the isotope values of the soil water vapor (Soderberg et al., 2012). In the distillation and condensation processes, the Rayleigh model is widely used to explain the isotopic composition of water vapor and moisture transport as a function of the initial isotopic composition at the moisture source, the degree of evaporation and the condensation temperature (Salamalikis et al., 2015; Tsujimura and Tanaka, 1998; Yoshimura, 2003).

In this study, we tried to use the micro-lysimeters to estimate evaporation under plastic film mulch, since micro-lysimeters have been widely used to measure evaporation in bare soil since they were simple, low-cost and relatively accurate (Allen, 1990; Li et al., 2013; Zhang et al., 2011b; Zhao et al., 2015). We quantitatively described the processes of the soil water and vapor exchange between the top soil and plastic mulch based on soil water balance, isotopic mass balance and the Rayleigh equation. The specific objectives were: (1) to identify the temporal characteristics of isotopic variation in shallow soil water and the evaporation vapor; (2) to clarify the mechanism of soil water movement and its vapor exchange under plastic film mulch; and (3) to quantify the evaporation from soil surface and the second evaporation from condensation water adhered in plastic film.

2. Fundamentals and theories

The stable water isotopes ^{18}O and D are measured in the unit of parts per thousand (‰) relative to the standard mean ocean water (SMOW), the isotopic compositions are calculated as follows:

$$\delta^{18}O(or\delta D) = \left(\frac{R_{sample}}{R_{standard}} - 1\right) \times 1000 \quad (1)$$

where R_{sample} and $R_{standard}$ are the $^{18}O/^{16}O$ (or D/H) molar ratios of the sample and standard water (SMOW), respectively.

As for the H and D, and ^{16}O and ^{18}O, they have different physical and chemical properties due to the mass differences, which are manifested as a fractionation effect. When water changes from gas to liquid, the light isotopes preferentially enrich in the gas. But when water changes from liquid to gas, the heavy isotopes preferentially enrich in the liquid. The fractionation is expressed as:

$$\alpha_{A\text{-}B} = R_B/R_A \quad (2)$$

where α is the isotope fractionation factor, R is the isotope ratio and the subscripts A and B represent gas and liquid (or liquid and gas) phase, respectively. When $\alpha_{A\text{-}B} < 1$, the heavy isotopes are depleted in phase B. When $\alpha_{A\text{-}B} > 1$, the heavy isotopes are enriched in phase B.

As water phase changes, the evolution of the isotopic composition is described by a Rayleigh equation with fractionation factor α (Rayleigh, 1896; Tsujimura and Tanaka, 1998; Yoshimura, 2003) as:

$$\frac{R_f}{R_i} = \frac{1 + 10^{-3}\delta_f}{1 + 10^{-3}\delta_i} = \left(\frac{W_f}{W_i}\right)^{\alpha-1} = f_0^{\alpha-1} \quad (3)$$

where δ is water isotopic composition of ^{18}O (or D), W is the amount of water in the final phase, f_0 is the fraction of remaining water, and the subscripts *i* and *f* represent the initial and final phases, respectively.

In this study, the process of soil evaporation under plastic film mulch can be determined by three steps: (1) the soil water changes from liquid to vapor; (2) the evaporation vapor changes to be condensation water adhered in plastic film; and (3) the condensation water evaporates again and through the perforated film mulches by vapor phase.

Therefore, for the first step, the distillation process, isotopic ratios of initial soil water and remaining water are given by:

$$R_{Lr}/R_{Li} = f_1^{\alpha_{L-V}-1} \quad (4)$$

where f_1 is the fraction of remaining soil water, and the subscripts Lr and Li represent remaining water and initial water, respectively. Using the δ values as shown by Eqs. (1), (4) can be rewritten as:

$$(10^{-3}\delta_{Lr}+1)/(10^{-3}\delta_{Li}+1) = f_1^{\alpha_{L-V}-1} \quad (5)$$

For the second step, the condensation process, relationship between the isotopic ratio of the initial vapor and the remaining vapor is given by:

$$R_{Vr}/R_{Vi} = f_2^{1/\alpha_{L-V}-1} \quad (6)$$

where f_2 is the fraction of remaining vapor, and the subscripts Vr and Vi represent remaining vapor and initial vapor, respectively. Thus, it can be rewritten as:

$$(10^{-3}\delta_{Vr}+1)/(10^{-3}\delta_{Vi}+1) = f_2^{1/\alpha_{L-V}-1} \quad (7)$$

Similarly, for the distillation process of the third step, the relationship between the isotopic composition of the initial condensation liquid water and the remaining condensation water can be determined as:

$$(10^{-3}\delta_{CLr}+1)/(10^{-3}\delta_{CLi}+1) = f_3^{\alpha_{L-V}-1} \quad (8)$$

where f_3 is the fraction of remaining condensation water, and the subscripts CLr and CLi represent remaining condensation water and initial condensation water, respectively.

The fractionation factor from liquid to vapor $\alpha_{L\text{-}V}$ can be calculated with soil temperature (Cappa et al., 2003; Majoube, 1971) as:

$$\alpha_{L-V}(^{18}O) = \frac{1}{1000}(1.137 \times 10^6/T^2 - 0.4156 \times 10^3/T - 2.0667) + 1 \quad (9)$$

Thus, the fraction of soil liquid water evaporating to vapor, the fraction of evaporation vapor changing to condensation water, and the fraction of condensation water evaporating to vapor should

Table 1
Methods of determining evaporation (E).

Methods	Method Desc
E(LB)	Measured by micro-lysimeter with bared soil
E(LM)	Measured by micro-lysimeter with plastic film hole
E(LB × HR)	Estimated by E(LB) × Plastic film hole rate
E(Iso)	Based on isotope measurement and modeling
E(F-B)	Calculated by sap-flow and soil water balance (ET-T)

be (1-f_1), (1-f_2) and (1-f_3), respectively. During the processes, we assume that the amount of vapor between soil surface and plastic mulch remain constant. Therefore, the total evaporation ratio (f_t, the fraction of total evaporation vapor from soil through plastic film holes) can be determined by:

$$f_t = (1\text{-}f_1)(1 - f_2)(1 - f_3) \tag{10}$$

3. Materials and methods

3.1. Experimental site

The experiment was carried out in a maize field, located at the Experimental Station of China Agriculture University in the Shiyang river basin of north-west China (37°52′ N, 102°51′ E, altitude 1581 m) during the 2015 seasons. The site is in a typical continental temperate climate zone, with a mean annual precipitation of 164.4 mm and mean annual pan evaporation about 2000 mm, annual temperature of 8 °C and annual sunshine duration of over 3000 h. Water is in severe shortage in this region, where the water table is 30–40 m below the ground surface. The experimental soil texture is loamy in top soil and sandy loam in lower soil, with a mean soil dry bulk density of 1.51 g/cm^3 and field capacity of 0.28 cm^3/cm^3 (Wu et al., 2016b).

3.2. Experimental design

Maize was planted with row spacing of 50 cm and plant spacing of 20 cm. The plant density was about 66,600 plants per hectare. Crop was sowed on 20 April and harvested on 15 September 2015. The growth stages of maize can be divided by early growth stage (DOY 110–159. DOY, day of year), middle growth stage (DOY 160–208) and late growth stage (DOY 209–257). The field experiment consisted of 3 plots with three replications. Each plot was 4 m × 100 m. The field was covered with plastic film with hole located above each seed (Fig. 1). The diameters of the holes were about 3.0 cm since they were perforated by a same maize planter. Thus, the total area of the holes took up 0.5% of the area of the plastic film. Considering the destruction of plastic film (e.g. by weeds, wind and farmer activities) during growth stage, the ratio of this area was about 0.5–5.0% at a rough estimate using ruler and photo analysis. Photos were taken randomly in the field and Photoshop software was used to estimate the area of the holes. The holes also provided channels for irrigation and rain water to infiltrate into soil. The precipitation and irrigation quota during the whole growing season were 117.8 mm and 172.0 mm (Fig. 6), respectively.

In this study, isotope-based method and three micro-lysimeter based methods were used to quantify soil evaporation (E), and the soil water balance method combined with the sap flow method was used to verify this quantification (Table 1).

3.2.1. Micro-lysimeters

Eighteen micro-lysimeters (MLs) were used to measure evaporation in the maize field, with nine having bare soil without mulch and another nine with plastic mulch. The ones with plastic mulch had similar ratio of hole area as in the field (Fig. 1). The details of three micro-lysimeter methods were described in Table 1. Each micro-lysimeter was made of PVC tubes, with a diameter of 10 cm and a height of 20 cm. The micro-lysimeters were installed in field according to Zhao et al. (2015) and Li et al. (2013). They were weighed daily (and hourly during isotope sampling days) to calculate water loss gravimetrically using electronic balances. The micro-lysimeters were reinstalled within one day after each irrigation and heavy rain, and no measurements were conducted during the irrigation or precipitation events. To investigate the effect of reinstalling soil and unchanging soil instead of sealed by filter paper on soil evaporation measurement, one comparative experiment were conducted with one treatment reinstalled every 3–5 d, and compared with unchanged treatment. The difference between two methods was very close ($E_{reinstalled} = 1.03E_{unchanged} - 0.09$, $R^2 = 0.91$). Thus, to avoid largely destroying the plastic film mulch in the field, the unchanged micro-lysimeter was used, and they were only sealed by filter paper, which can ensure the water exchange between the soil inside and outside the container.

3.2.2. Sap flow

Plant transpiration (T) was determined using sap flow system (Flow32–1 K system, Dynamax, Houston, TX, USA). Eight maize plants were randomly chosen within a 30 m diameter in the field, and sap flow was monitored during DOY 158–248 in 2015. The gauges were installed at a height of >0.2 m above the ground surface on the maize stem. The sensors were disconnected before irrigation and rain and reinstalled within 2–3 days after irrigation and rain in case of flooding and damaging for the sensors (Zhang et al., 2011a; Zhao et al., 2015). Gauge output were measured every 60 s and recorded as 15-min averages with a CR1000 data logger. Sap flow (L d^{-1}) was scaled to plant transpiration (mm d^{-1}) using the average ground area of each maize plant, and the field transpiration was averaged from the eight monitored plants.

3.2.3. Soil water balance

Crop evapotranspiration (ET; mm) was calculated by the water balance equation (Li et al., 2013; Rana and Katerji, 2000):

$$ET = P + I + Q - R - D - (W_{t_1} - W_{t_0}) \tag{11}$$

Where P is the total rainfall during the growing period; I is the amount of irrigation water; Q is the contribution from groundwater; R is the surface runoff; D is the deep drainage; W_{t0} and W_{t1} is the amount of soil water stored at 0–100 cm soil layer at time t_0 and t_1, respectively. All the units of the variable above are mm.

The surface runoff (R), the deep drainage (D) and contribution from groundwater (Q) were considered negligible since the experimental site was flat and the precipitation and irrigation was not intensive, and the groundwater depth was over 30 m. So the soil water balance Eq. (11) can be simplified as:

$$ET = P + I + (W_{t_1} - W_{t_0}) \tag{12}$$

W_{t0} and W_{t1} were monitored by the ECH_2O sensors (5TE, Decagon Devices Inc., Pullman, USA), which monitored the volumetric soil water content and the soil temperature continuously, and collected every 15 min using a data-logger (Environmental logging system, Decagon Devices, Inc., USA). The ECH_2O sensors with three replications were distributed in soil depths of 5, 10, 20, 40, 60, 80 and 100 cm, respectively.

3.2.4. Isotopic sampling and measurements

The soil samples were collected with a bucket auger at depth of 0–5, 5–10 and 10–20 cm, and water were extracted using the vacuum extraction system (LI-2000, LICA, China). Water vapor samples of soil evaporation were collected using a cold-trap multi-channel equipment (AWVCT04, LICA, China) as shown in Fig. 2. Condensation water samples were collected using injection syringes. All

Fig. 1. Maize field under plastic film mulch and micro-lysimeters. (a)Plastic film mulch and holes, (b)Micro-lysimeters and mulched-hole.

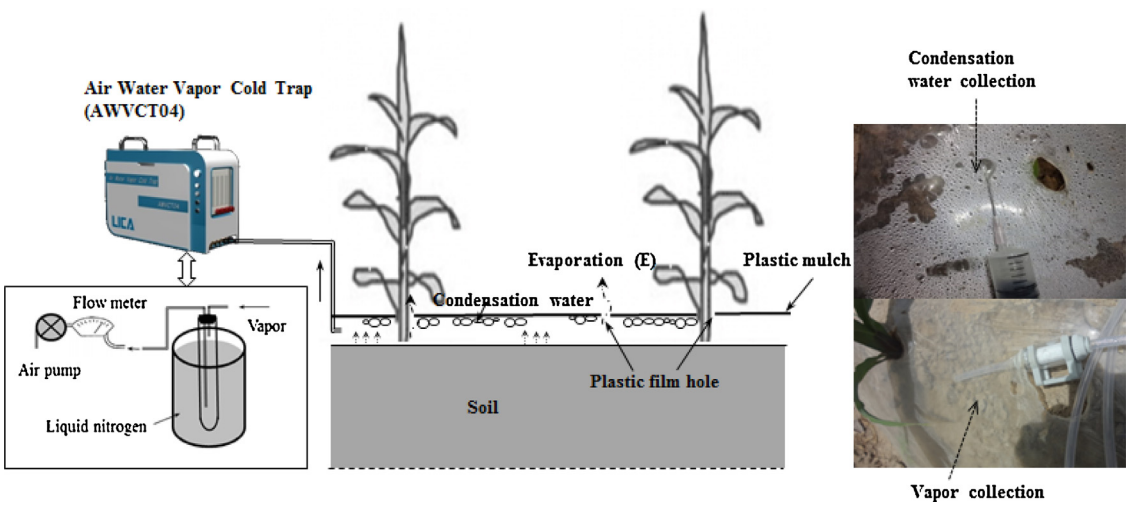

Fig. 2. Field experiment configurations for water vapor samples collection.

of the samples were collected with three replications, each water sample was stored in airtight container at 4 °C. The stable isotopic compositions (δD and $\delta^{18}O$) of the water samples were measured by Liquid-Water Isotope Analyzer (PICARRO L2130i, Picarro, USA).

4. Results and discussion

4.1. Soil evaporation determined by micro-lysimeter methods

Diurnal and seasonal variations of evaporation determined by three micro-lysimeter methods are shown in Fig. 3. The evaporation of E(LB × HR) (estimated by bare soil evaporation × hole-rate) was obviously lower than E(LM) (measured by micro-lysimeter with plastic film hole), and E(LB) (measured by micro-lysimeter with bare soil) was not much higher than E(LM), even though the micro-lysimeters were mulched of 95.0–99.5% by plastic film in E(LM) method. This indicated that the evaporation under plastic film mulch should be relative high, and there would be some deviation in E(LB × HR) method to estimate soil evaporation under plastic film mulch. However, previous study (Li et al., 2013) reported that it was feasible using micro-lysimeters to measure evaporation under plastic film mulch. They considered plastic film has a width of 1.1 m with a spacing of 0.45 m (bare-soil-rate was about 29%), thus evaporation under plastic film mulch can be calculated by 29% of the bare soil evaporation. The evaporation rate was 0.2–0.8 mm/d estimated by Li et al. (2013), which was lower than our E(LM) method with 0.6–1.3 mm/d but much higher than our E(LB × HR) method with 0.05–0.08 mm/d. This discrepancy may come from the difference of plastic film mulch pattern, which soil was completely mulched in our study while partly mulched in Li et al. (2013), and evaporation from the open-hole above each seed may be a relative large value which have been underestimated in E(LB × HR) method.

For the diurnal variations (Fig. 3a), evaporation in E(LM) was higher than that of E(LB) in the morning and at late afternoon. It was probably because soil surface moisture was higher under plastic film mulch in the morning due to compensation of condensation water adhered in plastic film at the previous night, and the soil temperature decreased slowly with film mulch at late afternoon causing evaporation deceased slowly but rapidly decreased in bare soil. Similar diurnal variations of bare soil evaporation were found in Zhao et al. (2015), who used micro-lysimeters in a vineyard and indicated that soil evaporation measured by micro-lysimeter can provide reliable measurements of hourly and daily ET components. For the seasonal variations (Fig. 3b), evaporation with high value of 1.33–1.45 mm/d at early stage, due to low vegetation cover and the strengthening of direct solar radiation. At middle growth stage,

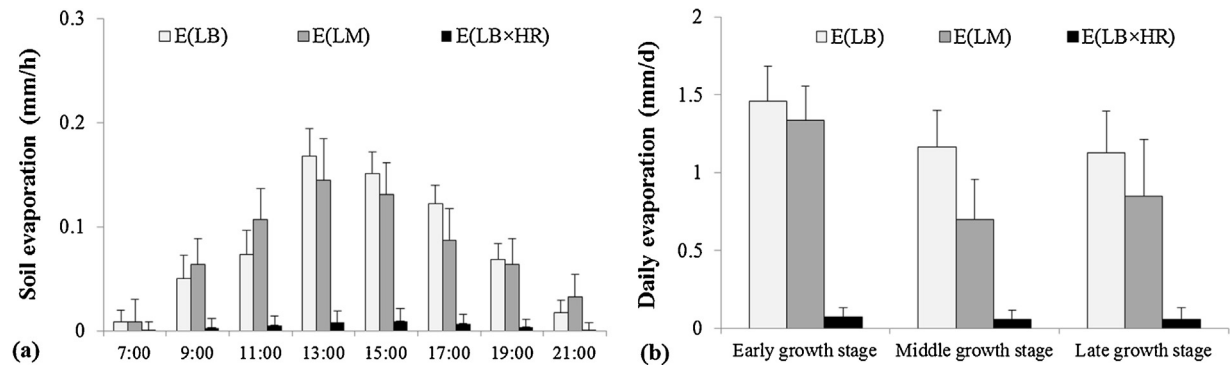

Fig. 3. Soil evaporation determined by three micro-lysimeter methods, (a) diurnal variations, and (b) seasonal variations. (E(LB), measured by micro-lysimeter with bared soil; E(LM), measured by micro-lysimeter with plastic film hole; E(LB × HR), estimated by E(LB) × Plastic film hole rate).

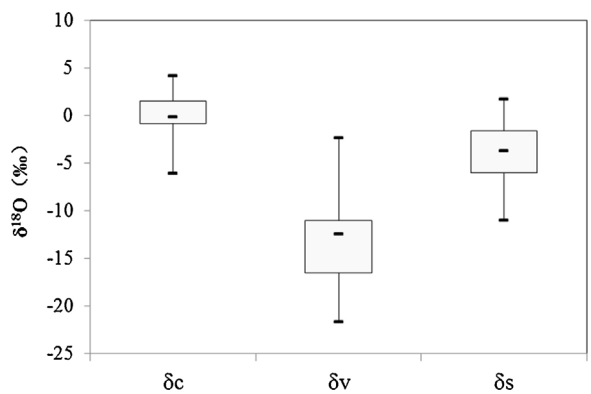

Fig. 4. Isotope composition distribution of condensation water (δ_C), evaporation vapor (δ_V) and soil water (0–20 cm) (δ_S) during the whole growing season.

evaporation rate was low with values around 0.69–1.12 mm/d, and slightly increased to 0.85–1.13 mm/d at late stage. E(LM) was close to E(LB) at early stage, which maybe because the stronger evaporation at this stage resulted in high concentration of condensation water under plastic film, and therefore resulted in higher surface soil water content than bare soil.

Although measured evaporation in bare soil using micro-lysimeters was feasible, there would be some deviation using the method in the field with plastic film mulch, since it was a complicated process that the second evaporation occurred in condensation water adhered in plastic film along with the process of soil water and evaporation vapor exchange, and the areas of the holes in the plastic mulch was difficult to quantify accurately (Li et al., 2003). Thus, we further clarified this mechanism by quantitatively explaining the processes using isotope-based method and soil water balance.

4.2. Isotope-based method for quantitatively explaining the processes of evaporation under plastic film mulch

The distribution of three water isotopic compositions at the seasonal scale is shown in Fig. 4. Significant differences were found in the isotopic compositions between condensation water (δ_C) and evaporation vapor (δ_V), their distributions ranged from −6.14‰ to 4.08‰, and −21.65‰ to −2.37‰, with the mean of −0.19‰ and −12.43‰ respectively. Condensation water had achieved the highest isotopic compositions due to isotope fractionation in condensation process causing the heavy isotopes ($\delta^{18}O$) enriched in liquid water (Rayleigh, 1896; Yoshimura, 2003). The low isotopic compositions and its large distribution range in the evaporation vapor were caused by isotope fractionation in distillation process, and the heavy isotopes were depleted in vapor. Besides, the turbulent component of the kinetic fractionation in the evaporation process may largely influence the isotopic compositions of vapor (Dubbert et al., 2013). The stronger isotopic enrichment was also found in the shallow soil (0–20 cm), which ranged from −11.04‰ to −1.68‰, with the mean of −3.74‰. Soil water evaporation resulted in stronger fractionation in oxygen isotopes (Allison and Hughes, 1983; Braud et al., 2009; Meißner et al., 2013).

Temporal dynamics of soil water, condensation water and evaporation vapor isotopic compositions at the daily scale are shown in Fig. 5. No large variation were observed among different growth stage for the distribution pattern of the same water isotopic compositions. For example, $\delta^{18}O$ in different water presented laminar distribution in the early growth stage. The $\delta^{18}O$ followed the order of $\delta_C > \delta_{S(0-5cm)} > \delta_{S(10-20cm)} > \delta_V$, but it seemed turbulent in $\delta_{S(5-10cm)}$. There were strong diurnal variations in the condensation water (δ_C) and evaporation vapor isotopic compositions (δ_V) (Fig. 5a), δ_C increased from early morning to midday and decreased from midday to late afternoon, but the δ_V showed an inverse pattern. The main reason is that the strongest evaporation in midday (13:00) resulted in the strongest isotope fractionation causing the heavy isotopes ($\delta^{18}O$) enriched in liquid water (δ_C) and depleted in vapor (δ_C) (Braud et al., 2009; Dubbert et al., 2013; Rayleigh, 1896). The results suggested that heavy isotope depleted and enriched alternately along with the processes of condensation and distillation, it was enriched again when the second evaporation occurred in condensation water.

For the shallow soil water at 0–5 cm layer, there was a decrease trend from early morning to midday and an increase trend from midday to late afternoon. While the isotopic composition for soil water at 10–20 cm layer ($\delta_{S(10-20cm)}$) showed an inverse pattern, although they had similar values at midday. However, at 5–10 cm layer, there were no very clear diurnal variations, with a maximum value in midday, and it was higher than both $\delta_{S(0-5cm)}$ and $\delta_{S(10-20cm)}$. It indicated that the soil evaporating front was presented in 5–10 cm soil layer, then the evaporation vapor were adsorbed by 0–5 cm soil layer, and the exchange motions of water molecules had occurred before it diffused to the outside.

Similar results were found in Yamanaka and Yonetani (1999), who evaluated the effect of soil moisture on the evaporation from bare soil surfaces using stable isotopic techniques, suggesting that evaporation and condensation occurs alternately within the dry surface layer (DSL) with diurnal cycle due to cyclic change in solar radiation and soil temperature, the evaporation zone consists of an arrow sub-zone around the bottom boundary of the DSL and a relatively wide sub-zone within the DSL. Similar results were found with Braud et al. (2009) and Dubbert et al. (2013), they indicated strongest isotopic enrichment was found in 2–5 cm soil depth, resulted from the turbulent component for the kinetic

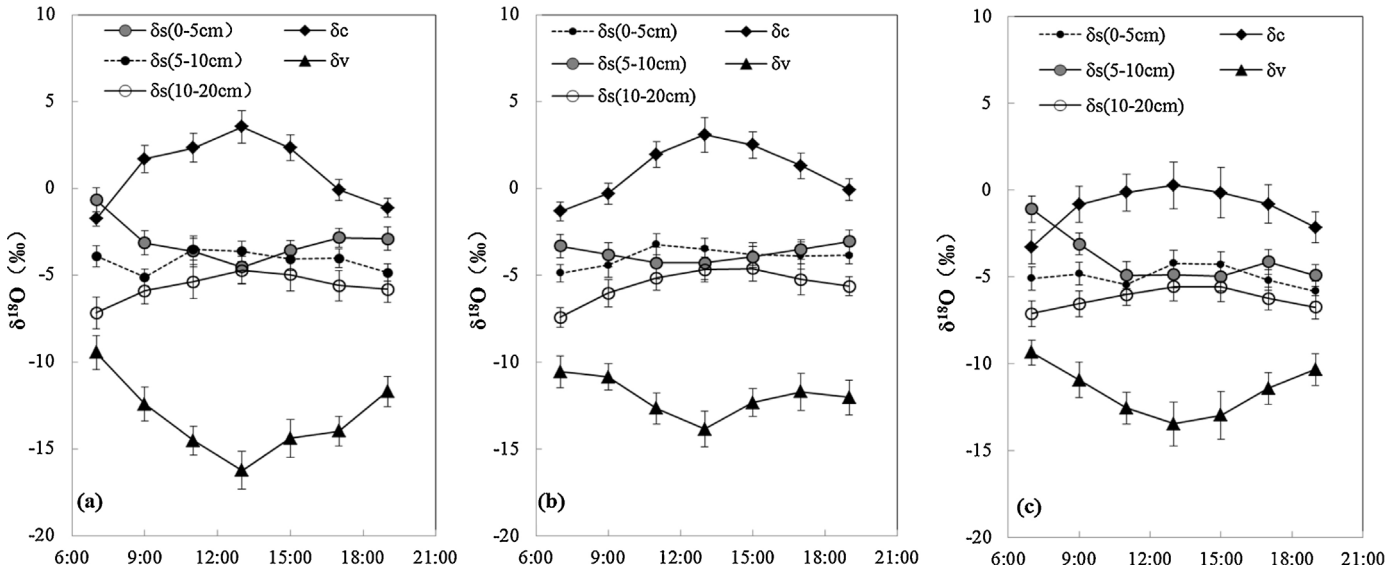

Fig. 5. Diurnal variations of the isotope compositions of condensation water (δ_C), evaporation vapor (δ_V) and soil water (0–10 and 10–20 cm) (δ_S) at (a) early growth stage, (b) middle growth stage, and (c) late growth stage.

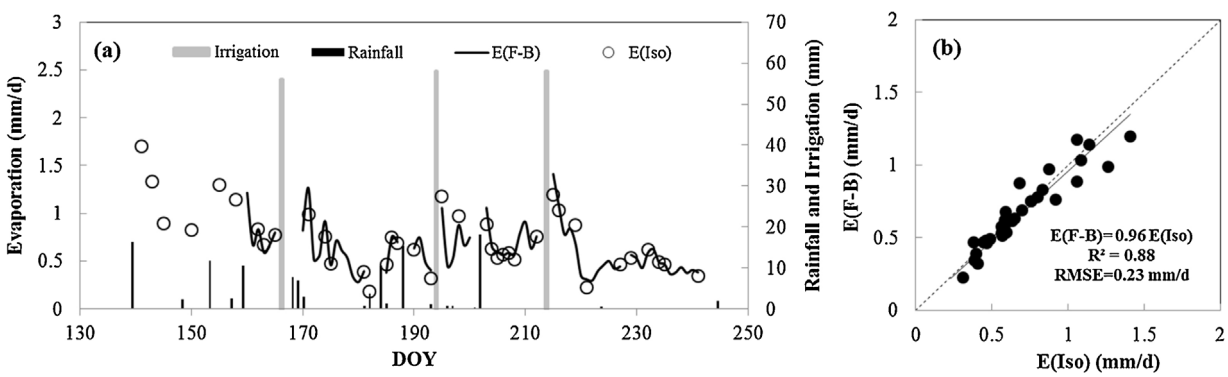

Fig. 6. Comparison of soil evaporation estimates between the isotopic method (E(Iso)) and sap flow combined with soil water balance method(E(F-B)).

fractionation, and the isotopic composition of evaporation was controlled by the isotopic composition of the liquid water within very thin soil surface layers when soil water transfer is dominant within the soil. However, those researches were most focusing on the bare soil or open-water, and few direct investigations of the evaporation from the soil surface have been conducted in field with plastic film mulch.

In order to present the mechanism more clearly, we quantitatively explaining the processes using the isotopic mass balance and the Rayleigh equation. The fractions of distillation and condensation during the water vapor exchange process are shown in Table 2. As have been described above, the ($1\text{-}f_1$, %) was the fractions of soil liquid water (0–20 cm) evaporated to vapor, thus, at early growth stage, with 5.1% of the soil water evaporated, 82.3% ($1\text{-}f_2$) of this evaporation vapor changed into condensation water and 77.8% ($1\text{-}f_3$) of this condensation water evaporated into vapor. Finally, the fraction of total evaporation vapor from soil through plastic film holes was 3.3% (f_t), estimated by the initial soil water content, the evaporation was about 1.18 mm/d at early stage, and the evaporation fraction (F_E, ratio E to ET) was about 38.2%.

Similarly, at the middle growth stage and late growth stage, with 1.7% and 2.0% of soil water was evaporated through plastic film holes, and the evaporation fraction (F_E) being 9.9% and 15.5%, respectively. During the whole growing season, with the mean of 4.5% of the soil water evaporated, 72.6% of the evaporation vapor were exchanged to condensation water and 70.0% of condensation water evaporated to vapor, with 2.3% of soil water evaporated through plastic film holes, and the evaporation rate was about 0.80 mm/d, the evaporation fraction (F_E) was about 21.2% (Table 2).

4.3. Comparison with sap flow and soil water balance methods and other studies

Soil water balance calculated evapotranspiration (ET) and sap flow determined transpiration (T) have been proved to be reliable (Cavanaugh et al., 2011; Han et al., 2015; Li et al., 2013; Mitchell et al., 2009; Rana and Katerji, 2000; Zhao et al., 2015). In this study, after forcing the energy balance to be closed (E = ET-T), we used these methods to verify evaporation quantification by isotope-based method. Fig. 6 shows that E(F-B) was close to E(Iso) during the maize growth season, the regression equation was E(F-B) = 0.95E(Iso) (R^2 = 0.88), with root mean square error (RMSE) of 0.23 mm/d (Fig. 6b), indicating a good agreement between the measured evaporation by two approaches. Thus, our isotope-based method to estimate evaporation under plastic film mulch was robust. Therefore, the evaporation rate was relative high (about 21.2%, ratio E to ET), although the proportion of the hole-rate of the plastic film mulch was small (0.5–5.0%). But it was often ignored by previous researchers.

Table 2
The fractions of distillation and condensation for the water vapor exchange process and evaporation quantification.

	Early growth stage	Middle growth stage	Late growth stage	whole growth stage (average)
f_1	0.949	0.957	0.960	0.955
f_2	0.177	0.359	0.285	0.274
f_3	0.222	0.379	0.297	0.300
f_t	0.033	0.017	0.020	0.023
E(mm/d)	1.178	0.580	0.649	0.803
ET(mm/d)	3.087	5.871	4.181	4.380
F_E	0.382	0.099	0.155	0.212

f_1 is the fractions of remain soil water, f_2 the fractions of remain evaporation vapor, f_3 the fraction of remain condensation water, f_t the fraction of total evaporation vapor from soil through plastic film hole, F_E the evaporation fraction (E/ET).

Compared with the results of micro-lysimeter methods (Fig. 3b), these isotope-based results were slightly lower than our E(LM) method and much higher than E(LB × HR) method. By compared with other studies, Li et al. (2013) reported that the evaporation in maize field with 72% of plastic film mulch estimated by micro-lysimeter and modeling methods was 0.2–0.8 mm/d, which was lower than our results by isotope-based method with mean value of 0.8 mm/d. Using micro-lysimeters placed below the plastic film in watermelon field to estimate evaporation, Xie et al. (2006) indicated that evaporation was about 51 mm (about 0.38 mm/d) and reduced by 78.0–93.7 mm in entire growing period when the gravel surface in field was mulched with 80% of plastic film. As reported by Han et al. (2015), evaporation in drip irrigation under plastic mulch could be reduced by 86.5% using the dual crop coefficient approach and soil water balance, where 85% of the field area was covered with plastic film. As we can see, there is no consensus as to which evaporation estimation methods are most accurate, also it is challenging to validate and benchmark the isotope-based methods. In review of previous studies on plastic film mulch, most of them were focusing on the effects of mulches on crop water use efficiency and production (Liu et al., 2009; Steinmetz et al., 2016; Wang et al., 2009; Xie et al., 2006), and on soil temperature, soil moisture, and surface microclimate (Han et al., 2015; Wang et al., 2009; Wang et al., 2016; Yang et al., 2012). Few direct investigations to determine evaporation rate from open-hole plastic film mulch in field and quantitatively explain the mechanism of soil water movement and its vapor exchange under plastic film mulch. We expect that future development of methods are able to accurately and continuously measure evaporation and evaluate its water vapor movement, so as to improve understanding of water cycling through the soil–plant–atmosphere continuum.

5. Conclusions

The paper presented a new set of field experiments aiming at estimating the evaporation (E) under plastic film mulch and clarifying its mechanism of soil water movement and vapor exchange based on soil water balance, isotopic mass balance and the Rayleigh equation. Micro-lysimeters-based methods and the sap flow combined with soil water balance method (E(F-B)) were conducted to compare to the evaporation quantification and verify the results. It showed that the isotope-based method was robust in estimating evaporation under plastic film mulch, but there would be some deviation using micro-lysimeter methods. Heavy isotope (^{18}O) depleted and enriched alternately along with the process of condensation and distillation, it was enriched again when the second evaporation occurred in condensation water adhered in plastic film. The soil evaporating front was presented in 5–10 cm soil layer, and the exchange motions of water molecules had occurred in 0–5 cm soil layer before diffusing to the outside. During the whole maize growing season, about 4.5% of the soil water (0–20 cm) evaporated, 72.6% of this evaporation vapor was condensed and 70.0% of this condensation water was evaporated again. About 2.3% of soil water evaporated through plastic film holes, with the mean evaporation rate of 0.80 mm/d, and the evaporation fraction (F_E, ratio of E to ET) was about 21.2%. That was, evaporation through small mulch holes was relative high and it should not be ignored. This quantitative analyses will improve our understanding of the mechanism of soil water movement and vapor exchange under plastic film mulch, and provide accurate estimation of evaporation in field, and it will be very useful for agricultural water management in similar arid areas.

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