



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



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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.

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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 per-

forated 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).

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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; Yopez 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:

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

where R_{sample} and R_{standard} are the $^{18}\text{O}/^{16}\text{O}$ (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:

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

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 $\alpha_{\text{A-B}} < 1$, the heavy isotopes are depleted in phase B . When $\alpha_{\text{A-B}} > 1$, 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:

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

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:

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

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

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

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:

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

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:

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

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

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

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

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