

Article

Using Stable Hydrogen and Oxygen Isotopes to Distinguish the Sources of Plant Leaf Surface Moisture in an Urban Environment

Yingying Xu *, Yan Yi, Xu Yang and Yingbo Dou

Key Laboratory of Songliao Aquatic Environment, Ministry of Education, Jilin Jianzhu University, Xincheng Street, District 5088, Changchun 130118, China; yiyianparticle@163.com (Y.Y.); yangxuwater@163.com (X.Y.); douyingbogas@163.com (Y.D.)

* Correspondence: xuyingying.1019@aliyun.com; Tel.: +86-0431-84566408

Received: 19 September 2019; Accepted: 28 October 2019; Published: 31 October 2019



Abstract: Plant leaf surface moisture is a frequent meteorological phenomenon that has complicated sources. As such, the determination of whether surface moisture is the input water or only the redistribution of water in the soil–plant–atmosphere ecosystem is of great importance. In this study, $\delta^{18}\text{O}$ and δD characteristic values of dew, guttation, and soil waters in *Buxus sinica* var. *parvifolia* M. Cheng were monitored during the frost-free period (June–September 2017) in Changchun, China, to differentiate the hydraulic relationship among atmospheric vapor, rainwater, soil, dew, and guttation waters and quantitatively distinguish the leaf surface moisture on the canopy and bottom of plants. The water vapor sources of the leaf surface moisture on plants' canopy and bottom were quantitatively verified in accordance with isotope fractionation and mass conservation principles. Results demonstrated that leaf surface moisture, atmospheric vapor, soil water, and dew were closely related. Leaf surface moisture was mainly the condensation of dew. The sources of canopy and bottom leaf surface moisture were basically the same. The proportions of canopy moisture from plant guttation, atmospheric vapor, and soil water were 2.4%–2.5%, 79.8%–92.4%, and 5.1%–17.8%, respectively. By comparison, the proportions of bottom leaf surface moisture were 0.6%–1.4%, 80.0%–93.0%, and 6.4%–18.6%, respectively. Leaf surface moisture is an important water input in urban systems. Moreover, the characteristic values of stable hydrogen and oxygen isotopes of urban dew are supplemented, and the transformation of atmospheric vapor, rainwater, and soil and dew waters is revealed.

Keywords: stable isotope; dew; vapor source; hydraulic relationship; transformation process

1. Introduction

The condensation of water on leaves is a common occurrence on urban plants in the morning. The sources of leaf surface moisture include dew and guttation [1]. Dew condensation is a normal weather phenomenon that can replenish the available moisture of plants and soil [2]. The unique landscape characteristics of an urban ecosystem result in the formation of a high amount of dew and a high degree of condensation [3,4]. Two main water sources are involved in dew formation. First is water vapor in the lower atmosphere (dewfall), which is the dominant source, and the other is water vapor that originates from flooded soil (dewrise) [5]. Guttation is the secretion of water and dissolved materials from the pores of plants, mainly at night. Dewfall is a kind of pure water input for plants, whereas dewrise (distillation) is only a part of soil, plant, and atmosphere system water redistribution.

Moreover, guttation is detrimental to plant growth because some nutrients can be utilized by fungi or insect pests. Therefore, the process of surface water circulation in urban ecosystems should be investigated to analyze the source of urban leaf surface moisture.

Hydrogen and oxygen isotope fractionation occurs in the water vapor cycle. Water bodies at different stages of the dew cycle have characteristic ^{18}O and D, which can be used as tracer elements to reveal specific information about the water cycle [6,7]. At present, isotope observations have been performed to analyze the ecological significance of dew. Liu et al. [8] and Wu et al. [9] analyzed the characteristic values of $\delta^{18}\text{O}$ and δD of dew water. They found that plant stomata are open at night and can directly absorb dew through the leaves. From the $\delta^{18}\text{O}$ in the leaf surface moisture, the foliar absorption of intercepted water (dew or rain) could be more important than previously appreciated, especially during drought [10]. Dew is an essential water source for plants in farmland, grassland, and desert areas. Amber et al. used a two-source isotope mixing model and found that *Salsola. inermis* Forssk, *Artemisia sieberi* Besser, and *Haloxylon scoparium* Pomel use 56%, 63%, and 46% of their water source from dew, respectively [2]. Corbin et al. conducted a similar study on perennial herbaceous plants in a grassland near the sea. They reported that 28%–66% of the water source of herbaceous plants comes from fog or dew [11]. These studies have focused on quantitatively determining the contribution of different water sources to plants. However, few studies have quantitatively distinguished the source of dew. Zhu and Jiang utilized stable isotopes (^{18}O and D) to determine the condensed dew from atmospheric vapor in the upper 20 cm of the soil layer [12]. Meng and Wen analyzed the δD and $\delta^{18}\text{O}$ characteristic values of dew in Hebei and Gansu in China and discovered that dew water is closely related to atmospheric vapor [13]. Liu et al. stated that the sources of fog-dew water in the Xishuangbanna region include pond, river, water vapor from water in soil, and water vapor produced during plant respiration [14]. However, these studies have remained in the qualitative analysis phase, and studies have yet to fully quantitatively analyze the source of leaf surface moisture. Wen et al. reported that isotopic labeling found in dew involves water vapor from the upper canopy (98%), from the evaporation of water in soil, and the transpiration of leaves in the lower canopy (2%) [5]. Using the same method, Kim and Lee reported that 72%–94% of the leaf surface moisture in some dry land crops (e.g., soybean, wheat, cotton, and corn) originates from dew, and only about 10% of the leaf surface moisture comes from plant stems [15].

Leaf surface moisture is an environmental factor of the urban ecosystem, and the sources of water vapor condensing on the leaves of urban plants at different heights may vary greatly [5,16]. The unclear leaf surface moisture source limits the research and discussion on the corresponding ecological effect. Identifying the source of water on the leaves of plants at different heights is helpful for exploring the water circulation process of the urban surface layer. Further clarifying the mechanism of dew formation is also helpful. Therefore, the water source of urban leaf surface moisture should be studied, and guttation and dew (atmospheric vapor and soil water) should be distinguished. This study analyzed the characteristics of stable hydrogen and oxygen isotope values of rainwater, soil water, dew, and leaf surface moisture of plants at different heights. This study also applied the isotope mass conservation law (mass balance equation) to explore the relationship among different water types. Furthermore, this study quantitatively calculated the contribution of various sources of the leaf surface moisture.

2. Materials and Methods

2.1. Study Site

The experimental plot was located in Changchun, which lies in the northeast portion of China (44°15' N; 126°18' E). Changchun is in a semi-humid monsoon climate zone with a mean annual temperature of 4.8 °C and an annual amount of precipitation of 522–615 mm. The rainy season from July to September causes warm and humid climatic conditions (Figure 1). Changchun has four distinct seasons. In comparison with strong winds in spring and freezing conditions in winter, high humidity, large temperature difference between day and night, and wind speed of below 2 m/s are experienced in summer and autumn.

Therefore, the climatic conditions are suitable for dew condensation. Annual dew days can be up to 130 days or more, and the annual dewfall is about 23–35 mm [17]. Our observation was carried out at the mature stage of plants (from early June to late September in 2017). The experimental plot site was specifically located in Jilin Jianzhu University, which is in the southeast of Changchun City. *Buxus sinica* var. *parvifolia* M. Cheng was selected as a representative plant type. Its maximum leaf area index was 12.57 cm²/cm², and its maximum canopy height was 1.5 m.

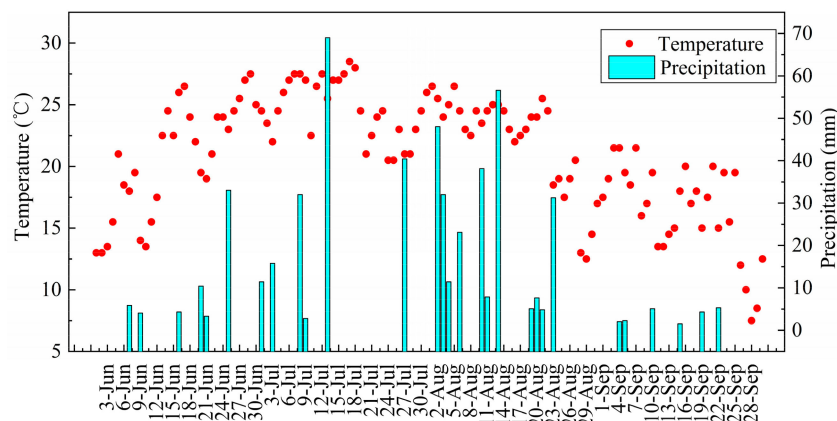


Figure 1. Temperature and precipitation from June to September 2017.

2.2. Sample Collection

During the experiment, rainwater samples were collected on every rain event. Leaf surface moisture samples from the canopy/bottom of the plant were collected when the leaf surface moisture was heavy. Atmospheric vapor, canopy/bottom guttation and dew, and surface soil water, along with the leaf surface moisture samples, were obtained. A total of 30 rain samples and 10 samples each of plant canopy/bottom dew, canopy/bottom guttation, soil water, and atmospheric vapor were collected during the experimental period. According to the principle of Rayleigh isotope fractionation, fractionation is related to environmental temperature and humidity [5]. Isotope fractionation occurs naturally with each cycle of evaporation and condensation. All the samples were obtained from the same place to ensure that the samples of guttation, soil water, atmospheric vapor, leaf surface moisture, and dew were collected under the same conditions. The dew, guttation, atmospheric vapor, and leaf surface moisture samples from the bottom and the canopy were collected at heights of 0.15 and 1.2 m above the ground, respectively:

- Leaf surface moisture: Leaf surface moisture was directly collected from plant leaves in situ in the morning using a needle to avoid contamination during the collection process. The samples were sealed in 50 mL plastic bottles.
- Dew: Dew condensation depends on meteorological factors [18,19]. Dew is the highest in July and August in Changchun, so collecting dew samples in these months was convenient. Dew samples were collected using a special collector (beaker made of Teflon) 30 min before sunrise from the beginning of July to the beginning of September.
- Atmospheric vapor: In the dew condensation period, an air condensation compressor (rotating speed = 100–120/s) was used to collect the condensed liquid water of the atmospheric vapor. About 10–15 mL of water was sampled at each time.
- Guttation: The collection of guttation was difficult, and the evaporation of surface water under different temperatures and humidities caused variations in the degree of isotope fractionation. Therefore, the experiment was conducted in situ. The leaves were washed with distilled water at sunset before guttation formed in order to avoid the disturbance of dust on the leaves. The plant leaves were then immediately covered with a plastic bag (l × w = 0.5 m × 0.3 m). The bottoms of the bags were sealed to prevent the entry of vapor from the atmosphere into the plastic bag.

The amount of guttation was small. Some parts condensed in the bag, whereas other parts still clung to the rice leaves during collection. The stems of *B. sinica* were lightly shaken until the guttation on the leaves dropped into the bag to collect the guttation that still clung to the leaves at sunrise. The water in the bag was considered guttation. Each sample was 5–10 mL.

- Soil water: The surface soil samples (0–20 cm) were collected and sealed. An automatic vacuum condensation extraction system (LI-2100) was used to heat and distill water in the soil in an ultra-low-pressure environment and extract water in a low-temperature environment (Figure 2). The principles of ultra-low-pressure vacuum distillation and freezing were applied. Water was collected through condensation at a low temperature without fractional distillation, and 10–15 mL was extracted at a time.
- Rain: Precipitation samples were collected in plastic bottles. The samples were collected immediately after each rain event and then sealed in 100 mL polyethylene bottles to prevent evaporation.

2.3. Sample Measurement

Analyses were carried out in a laboratory at the Institute of Northeast Geography and Agroecosystem, Chinese Academy of Sciences. $\delta^{18}\text{O}$ and δD in each sample were immediately measured using a liquid water isotope analyzer (LGR, LWIA-24d; USA) (Figure 2). The precisions of $\delta^{18}\text{O}$ and δD between the samples and the Vienna Standard Mean Ocean Water were below $\pm 0.2\text{‰}$ and $\pm 0.6\text{‰}$, respectively. The wind direction data were provided by the automatic weather station (MK-III-LR, USA) and recorded at 1 h intervals.

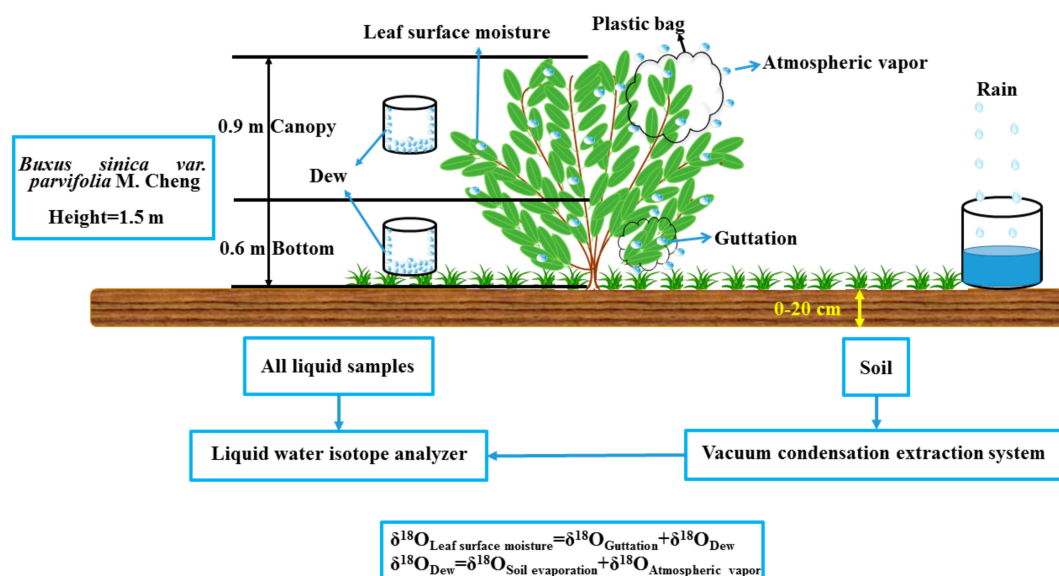


Figure 2. Schematic of sample collection and analysis.

2.4. Data Analysis

The source of leaf surface moisture was quantitatively determined using the samples' δD or $\delta^{18}\text{O}$. The sources mainly included dew and guttation. Dew mainly comprised atmospheric vapor and soil evaporation water. The two-end-member mixing model was expressed as follows:

$$\delta_{\text{sample}} = X\delta A + (1 - X)\delta B, \quad (1)$$

where X is the mix ratio of types A and B water, δ_{sample} is δD or $\delta^{18}\text{O}$ of the mixture, and δA and δB are δD or $\delta^{18}\text{O}$ of types A and B water, respectively. The formula suggests that the mix ratio of the two types of water could be confirmed after samples of both types were collected and analyzed. Using

the isotope data from the surface moisture and the water sources, we performed two passes of the two-source linear model to determine the proportional use of different water sources. The first time was to distinguish dew source, and second time was to determine the leaf surface moisture.

2.5. Air Mass Back Trajectory Cluster

The 2-day backward trajectories arriving at Changchun were calculated using a National Oceanic and Atmospheric Administration HYSPLIT model with a $2.5^\circ \times 2.5^\circ$ latitude–longitude grid. In this study, considering the condition of the surface layer in the urban ecosystem, the arrival level was set at 500 m above the ground because 500 m is the lowest altitude of precipitation clouds. It could cover all the previous airflow (0–5000 m) in 48 h if we set 500 m as the ending level. The back trajectories were widely considered to determine potential moisture sources [20–22], and the HYSPLIT model was run when rain occurred at the sampling site.

3. Results and Discussion

3.1. Characteristics of $\delta^{18}\text{O}$ and δD in Each Type of Water

$\delta^{18}\text{O}$ in the precipitation ranged from -11.1‰ to -1.4‰ (mean = -5.0‰), whereas δD varied from -66.4‰ to -8.2‰ (mean = -39.7‰). The local meteoric water line (LMWL) is presented in Figure 3. The slope of LMWL ($\delta\text{D} = 7.93$, $\delta^{18}\text{O} = -0.04$) was close to the global meteoric water line ($\delta\text{D} = 8$, $\delta^{18}\text{O} = +10$), indicating that the equilibrium evaporation process occurred from early June to late September [23] in Changchun City, and sufficient water vapor was present in the atmosphere.

The isotopic values of guttation were below the LMWL and lower than those of other water bodies. Guttation is the direct secretion of liquid from plant leaves. Hydrogen and oxygen isotope fractionation does not occur when water becomes absorbed by plant roots and moves from roots to leaves [24,25]. The water absorbed by roots is mainly from soil water in the deeper layer [2,9] and has not undergone a strong evaporation process. This type of water has low $\delta^{18}\text{O}$ and δD . If guttation did not go through isotopic fractionation or only experienced slight fractionation, the value of hydrogen and oxygen isotopes in guttation was lower than that in other water bodies.

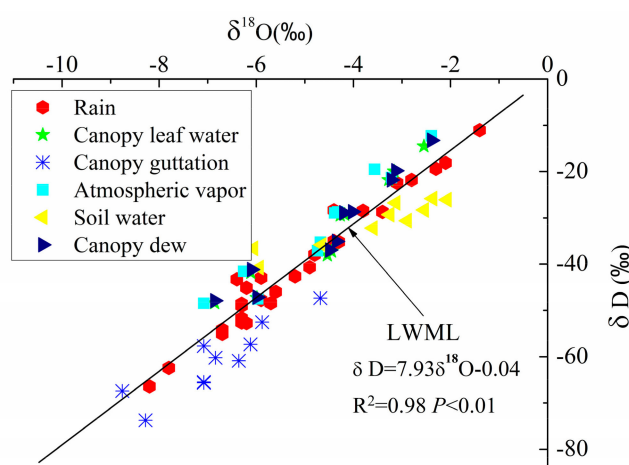


Figure 3. Stable isotopes of water by type and the local meteoric water line (LMWL) in Changchun.

Guttation was below the LMWL, but other water bodies (except soil water) were basically above the LMWL. This finding indicated that dew, atmospheric water, and leaf surface moisture evaporated. During evaporation, light water molecules (H_2^{16}O) are more active than heavy water molecules (H_2^{18}O or HD^{18}O). The former also escapes the liquid phase, and moisture is concentrated by evaporation. Consequently, water vapor contains more H and ^{16}O , and high $\delta^{18}\text{O}$ and δD are found in residual water [26,27]. Surface soil water was mainly from rain and did not undergo too much evaporation.

As a result, soil water was below the LMWL and close to GMWL. $\delta^{18}\text{O}$ and δD of dew were among guttation, soil water, and atmospheric vapor, and the values were close to the atmospheric vapor. Therefore, dew was a mixture of guttation, soil water, and atmospheric vapor. Dew mainly originated from atmospheric vapor.

3.2. Relationship between $\delta^{18}\text{O}$ and δD in Each Type of Water

$\delta^{18}\text{O}$ and δD in the precipitation initially increased and then decreased, presenting an N-shaped curve from June to late September (Figure 4). $\delta^{18}\text{O}$ and δD in atmospheric vapor, soil water, dew, and leaf surface moisture had the same trend of changes as those in precipitation. A significantly positive correlation was observed between leaf surface moisture, dew, and atmospheric vapor in both heights. For example, in terms of canopy height, $\delta^{18}\text{O}$ and δD in leaf surface moisture and dew had r values of 0.98 and 0.99, respectively. $\delta^{18}\text{O}$ and δD in leaf surface moisture and atmospheric vapor had r values of 0.96 and 0.98, respectively. This result was similar to the soybean canopy in the USA [16]. These findings demonstrated that the four types of water had a close hydraulic relationship. Precipitation is an important input to soil water, and vapor from soil and raindrop evaporation is an essential part of atmospheric vapor. Water vapor in the atmosphere at night is the main source of dew condensation.

In China, the stable isotope temperature effect in the northern part is more considerable than that in the southern part [28]. Isotopes in northeast China are positively correlated with local temperature [29,30]. Figure 4 shows that the precipitation isotopes were enriched in July, when a high temperature was recorded (Figure 1). However, the positive correlations between $\delta^{18}\text{O}$ and δD of precipitation and temperature were not very significant for all data because the stable isotopes in precipitation are controlled not only by temperature but also by regional climate background, such as monsoon [31]. Affected by the monsoon climate, $\delta^{18}\text{O}$ and δD in precipitation displayed a decreasing trend in August. The precipitation air mass in the study area mainly came from the inner continental region (Russia and Mongolia) in June and July, whereas the precipitation air mass in August mainly originated from the Pacific Ocean. Water vapor, including water vapor mixture from the Pacific Ocean and the Eurasian continent, in September was complex. $\delta^{18}\text{O}$ in precipitation reflects the source of water vapor [32]. Dry air and cold air from land bring additional precipitation with high $\delta^{18}\text{O}$, whereas ocean air carries precipitation with low $\delta^{18}\text{O}$ [33]. This phenomenon indicates that the temperature was the dominant factor affecting the variation in $\delta^{18}\text{O}$ and δD if the precipitation vapor source was similar. Moreover, different precipitation sources rather than temperature caused fluctuation in stable isotopes.

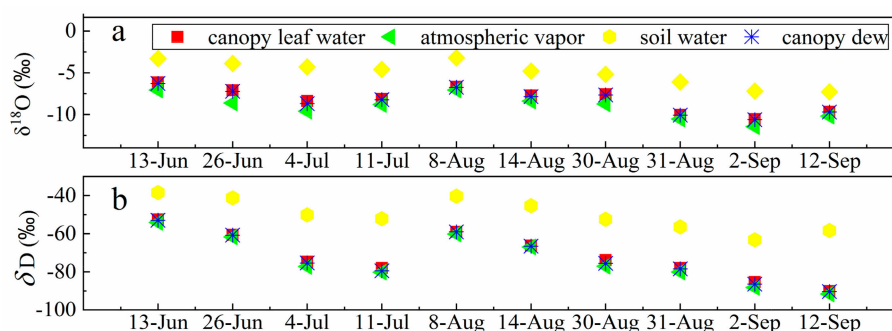


Figure 4. Seasonal variability of δD and $\delta^{18}\text{O}$ in different waters by type from different heights (2017): (a) Seasonal variability of $\delta^{18}\text{O}$ in canopy leaf water, atmospheric vapor, soil water and canopy dew; (b) Seasonal variability of δD in canopy leaf water, atmospheric vapor, soil water, and canopy dew.

3.3. Deuterium Excess in Precipitation and Its Tracing Significance

In precipitation, the effect of evaporation on the hydrogen–oxygen isotopic relationship in rain varies, which Dansgaard defines as deuterium excess ($d = \delta\text{D} - 8\delta^{18}\text{O}$) [34]. The d of the atmospheric precipitation in different regions can intuitively reflect the imbalanced degree of the

evaporation and condensation of atmospheric precipitation in a given region. This variable is an important comprehensive environmental factor index of atmospheric precipitation [35–37]. In general, the average d is 10‰, and it is correlated with the physical conditions of the oceanic source areas of precipitation. d is high if precipitation moisture comes from dry areas with a relatively low humidity. On the contrary, d is low if precipitation moisture comes from humid areas with abundant water vapor [32]. In our study, d was below the global average of 10‰. In general, sub-cloud evaporation decreases the d value [35]. The lower d (<10‰) suggested that raindrops strongly evaporated. The analysis of the isotopic values of rain from June to September revealed that the d of precipitation significantly changed between July and August. The air mass from the continental region contributed high d (up to 7.9‰) to precipitation in July, whereas the air masses from maritime regions yielded low d (up to −3.2‰) in precipitation in August (Figure 5).

The HYSPLIT model further verified the reliability of the water vapor sources characterized by hydrogen and oxygen isotopes in precipitation. As shown in the distribution of the backward trajectory in Figure 5, water vapor in June and July with a high d mainly came from water vapor in the northwest. When the Pacific Ocean's southeast monsoon arrived in August, the wind direction prioritized East wind in August, and d decreased. In September, the southeast monsoon receded, and d gradually increased.

Table 1 shows that the stable isotopes in Changchun were lower than those in the other sites. On the one hand, Changchun is at a high latitude and has a low temperature. According to the effects of stable isotope temperature and latitude [35], the rain stable isotope enriches $\delta^{18}\text{O}$ and δD in low-latitude and warm areas (e.g., Xishuangbanna, China). On the other hand, rain isotopes are depleted in inland areas but are enriched in coastal areas (e.g., Montpellier, France). Moreover, water in arid regions (e.g., Negev Desert, Israel) intensely evaporates, leading to precipitation isotope enrichment.

Differences in dew are controlled by background hydrological conditions [5]. As shown in Figure 2, changes in $\delta^{18}\text{O}$ and δD in dew, atmospheric vapor, and precipitation were almost the same because precipitation is an important source of atmospheric vapor. Although atmospheric vapor is not the direct source of dew, atmospheric vapor condenses and becomes dew during the night. In the process of evaporation from precipitation or the condensation of atmospheric vapor, isotope kinetic fractionation occurs [35]. However, the change in isotope value caused by kinetic fractionation is weaker than the contribution of advective vapor [38]. In conclusion, local precipitation should be a major source of dew, and hydrogen and oxygen isotopes in dew could reflect the different sources of precipitation.

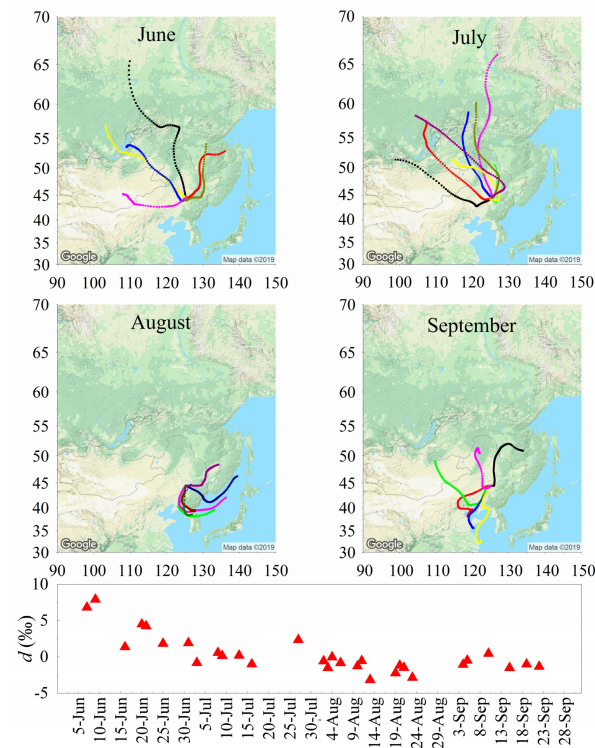


Figure 5. Trajectory map of air mass in typical rain events and δD from June 2017 to September 2017.

Table 1. Characteristic values of dew in different sites (‰).

Site	Changchun, China		Xishuangbanna, China		Luan Cheng, China				Montpellier, France		Minneapolis–St Paul, USA			Negev Desert, Israel				
Coordinates	44°15′ N, 126°18′ E		21°56′ N, 101°15′ E		37°50′ N, 114°40′ E				43°36′ N, 3°53′ E					34°46′ N, 30°51′ E				
Reference	This Study		[39]		[5]				[24]		[16]			[2]				
Plant Type	<i>Buxus sinica</i> var. <i>parvifolia</i> M. Cheng		Arbor		Wheat		Maize		Alfalfa		Soybean		<i>Salsola. inermis</i> Forssk		<i>Artemisia sieberi</i> Besser		<i>Haloxylon scoparium</i> Pomel	
	Mean $\delta^{18}\text{O}$	Mean δD	$\delta^{18}\text{O}$	δD	Mean $\delta^{18}\text{O}$	Mean δD	Mean $\delta^{18}\text{O}$	Mean δD	$\delta^{18}\text{O}$ at 4:00 in Summer	δD at 4:00 in Summer	Mean $\delta^{18}\text{O}$	$\delta^{18}\text{O}$	δD	$\delta^{18}\text{O}$	δD	$\delta^{18}\text{O}$	δD	
	−7.4 ± 1.5	−63.5 ± 12.5	−6.2 ~ 1.9	−30 ~ 27	−1.2 ± 2.4	−13.4 ± 16.7	−4.9 ± 1.5	−44.1 ± 10.4	−6.4	−17.8	−3.6 ± 0.6	−6 ~ −1	−22 ~ 10	−5.5 ~ 2.5	−20 ~ 11	−5.9 ~ 1.5	−21 ~ 12	

3.4. Sources of Canopy and Bottom Dew

The sources of canopy and bottom leaf surface moisture of *B. sinica* were basically the same (Table 2). The average proportions of canopy surface moisture from guttation, atmospheric vapor, and soil water were 2.4%–2.5%, 79.8%–92.4%, and 5.1%–17.8%, respectively, whereas the proportions of bottom surface moisture from guttation, atmospheric vapor, and soil water were 0.6%–1.4%, 80.0%–93.0%, and 6.4%–18.6%, respectively. Atmospheric vapor is the main source of vapor for canopy and bottom dew. Therefore, surface moisture is an important water input in urban systems.

This finding is different from the results of Xu et al. [40] and Luo et al. [41]. On the basis of the analysis on the source of paddy surface moisture, Xu et al. [40] found that guttation and atmospheric vapor respectively contribute 30% and 70% of vapor source to paddy surface moisture in Sanjiang Plain, China. Luo et al. [41] studied the effect of surface moisture and water temperature on rice leaf moisture penetration in the Philippines. They concluded that paddy guttation was almost equal to atmospheric vapor. Under the condition of sufficient soil moisture, high air humidity, and low wind speed and temperature, guttation spills out of leaves. This phenomenon always happens in gramineous plants such as rice, wheat, sorghum, maize, and willow trees. To maintain water balance, gramineous plants release surplus moisture through the formation of guttation. The guttation phenomenon of paddy is more obvious than that of *B. sinica*, and it is one of the reasons for the differences in vapor sources. Weather conditions in different areas cause differences in crop growth situations. Water in paddy can be continuously eliminated from the plant. When temperature is high, water in rice is released. If the outside temperature and humidity are high, roots absorb more water. However, high humidity prevents water evapotranspiration. Consequently, water leaks directly from the stomata. Therefore, the efficiency of root water absorption varies because of different temperatures, relative humidities, and plant varieties in various regions. As a result, the proportion of plant guttation in dew water varies.

Table 2. Leaf surface moisture sources of *B. sinica* in Changchun in 2017.

Date	Canopy Leaf Surface Moisture (%)			Bottom Leaf Surface Moisture (%)		
	Guttation	Atmosphere	Soil	Guttation	Atmosphere	Soil
June 13th	3.2 ~ 4.6	75.3 ~ 89.8	7 ~ 20.1	0 ~ 1.2	84.0 ~ 94.8	5.2 ~ 14.8
June 26th	0.5 ~ 2.3	68.9 ~ 95	4.5 ~ 28.8	0 ~ 2.3	87.9 ~ 94.4	5.6 ~ 9.8
July 4th	2.1 ~ 5.3	78.3 ~ 91.4	6.5 ~ 16.4	0 ~ 0.4	78.9 ~ 91.7	8.3 ~ 20.7
July 11st	2.1 ~ 4.7	84.6 ~ 93	2.3 ~ 13.3	1.8 ~ 2.3	68.3 ~ 87.6	10.6 ~ 29.4
August 8th	0 ~ 1.9	89.8 ~ 94.2	5.8 ~ 8.3	0 ~ 1.4	82 ~ 94	6 ~ 16.6
August 14nd	1.7 ~ 3.4	82.2 ~ 96.5	1.8 ~ 14.4	0 ~ 0.3	81.2 ~ 92.2	7.8 ~ 18.5
August 30th	2.3 ~ 6.7	67.9 ~ 87.4	5.9 ~ 29.8	1.4 ~ 2.8	78.3 ~ 92.5	4.7 ~ 20.3
August 31st	0.7 ~ 2.1	89.2 ~ 91.2	6.7 ~ 10.1	1 ~ 2.8	74.3 ~ 93.2	5.8 ~ 22.9
September 2nd	1.1 ~ 2.9	79.2 ~ 90.1	7 ~ 19.7	0.5 ~ 0.7	85.9 ~ 94.6	4.9 ~ 13.4
September 12nd	0.4 ~ 0.6	82.4 ~ 95.9	3.5 ~ 17.2	0 ~ 1.4	79.3 ~ 95.2	4.8 ~ 19.3
Average	$2.4 \pm 1.6(^{18}\text{O}) \sim 2.5 \pm 2.1(\text{D})$	$79.8 \pm 7.5(^{18}\text{O}) \sim 92.4 \pm 3.0(\text{D})$	$5.1 \pm 2.0(\text{D}) \sim 17.8 \pm 7.1(^{18}\text{O})$	$0.6 \pm 1.0(\text{D}) \sim 1.4 \pm 0.8(^{18}\text{O})$	$80.0 \pm 5.7(^{18}\text{O}) \sim 93.0 \pm 2.3(\text{D})$	$6.4 \pm 1.9(\text{D}) \sim 18.6 \pm 5.4(^{18}\text{O})$

a ~ b means the end values calculated by D and ^{18}O .

4. Conclusions

This study monitored the dew condensation in an urban ecological system to quantitatively analyze the sources of plant dew vapor in urban ecosystems and reveal the near-surface water vapor cycle. The following conclusions were obtained:

- (a) The trend of stable hydrogen and oxygen isotopes of rainwater, soil water, atmospheric vapor, and dew from the beginning of June to the end of September was basically consistent. Significant correlations were obtained between leaf surface moisture and atmospheric vapor or dew, thereby confirming that a hydraulic relationship existed among the four types of water.
- (b) $\delta^{18}\text{O}$ and δD of leaf surface moisture among soil water, atmospheric vapor, and plant guttation demonstrated that leaf surface moisture was composed of these three types of water. Rain was not directly part of the dew, but vapor condensation became an important part of the dew after water evaporated. Therefore, various air masses and moisture sources affected the isotope compositions of dew.
- (c) Atmospheric vapor contributed 81.8%–94.8% and 81.1%–93.6% vapor source to dew at the canopy and the bottom, respectively. The outside water vapor was the main source of urban plants' dew. Urban ecosystem dew condensation at night served as input water, which could be absorbed or replenished by plants during evaporation.

In the future, we will further strengthen our study on water vapor release in leaf surface moisture.

Author Contributions: Conceptualization, Y.Y.; methodology, Y.Y.; validation, Y.Y. and Y.D.; formal analysis, Y.Y.; investigation, Y.X. and Y.Y.; writing—original draft preparation, Y.Y. and Y.D.; writing—review and editing, Y.Y. and X.Y.; project administration, Y.Y.; funding acquisition, Y.Y.

Funding: This work was supported by the State Key Program for Research of China (project no. 2018YFD0800904), Special S&T Project on Treatment and Control of Water Pollution (project no. 2012ZX07408001), and Technology Program of Jilin Province (project no. 201705200827JH).

Conflicts of Interest: The authors declare no conflict of interest.

References

- Richards, K. Urban and rural dewfall, surface moisture, and associated canopy-level air temperature and humidity measurements for Vancouver, Canada. *Bound. Lay. Meteorol.* **2005**, *114*, 143–163. [[CrossRef](#)]
- Hill, A.J.; Dawson, T.E.; Shelef, O.; Rachmilevitch, S. The role of dew in Negev Desert plants. *Oecologia* **2015**, *178*, 317–327. [[CrossRef](#)] [[PubMed](#)]
- Gałek, G.; Sobik, M.; Błaśa, M.; Polkowska, Ż.; Cichała, K.K. Urban dew formation efficiency and chemistry in Poland. *Atmos. Pollut. Res.* **2016**, *7*, 18–24. [[CrossRef](#)]
- Beysens, D.; Mongruel, A.; Acker, K. Urban dew and rain in Paris, France: Occurrence and physico-chemical characteristic. *Atmos. Res.* **2017**, *189*, 152–161. [[CrossRef](#)]
- Wen, X.F.; Lee, X.H.; Sun, X.M.; Wang, J.L.; Hu, Z.M.; Li, S.G.; Yu, G.R. Dew water isotopic ratios and their relationships to ecosystem water pools and fluxes in a cropland and a grassland in China. *Oecologia* **2012**, *168*, 549–561. [[CrossRef](#)]
- Zhang, W.G.; Meng, J.Y.; Liu, B.; Zhang, S.C.; Zhang, J.; Jiang, M.; Lv, X.G. Sources of monsoon precipitation and dew assessed in a semiarid area via stable isotopes. *Hydrol. Process.* **2017**, *31*, 1990–1999.
- Scholl, M.; Eugster, W.; Burkard, R. Understanding the role of fog in forest hydrology: stable isotopes as tools for determining input and partitioning of cloud water in montane forests. *Hydrol. Process.* **2010**, *35*, 353–366.
- Liu, W.J.; Liu, W.Y.; Li, P.J.; Duan, W.P.; Li, H.M. Dry season water uptake by two dominant canopy tree species in a tropical seasonal rainforest of Xishuangbanna, SW China. *Agric. For. Meteorol.* **2010**, *150*, 380–388. [[CrossRef](#)]
- Wu, J.N.; Liu, W.J.; Chen, C.F. How do plants share water sources in a rubber-tea agroforestry system during the pronounced dry season. *Agric. Ecosyst. Environ.* **2017**, *236*, 69–77. [[CrossRef](#)]
- Breshears, D.D.; McDowell, N.G.; Goddard, K.L.; Dayem, K.E.; Martens, S.N.; Meyer, C.W.; Brown, K.M. Foliar absorption of intercepted rainfall improves woody plant water status most during drought. *Ecology* **2008**, *89*, 41–47. [[CrossRef](#)]

11. Corbin, J.D.; Thomsen, M.A.; Dawson, T.E.; D'Antonio, C.M. Summer water use by California coastal prairie grasses: Fog, drought, and community composition. *Oecologia* **2005**, *145*, 511–521. [[CrossRef](#)] [[PubMed](#)]
12. Zhu, Q.L.; Jiang, Z.B. Using stable isotopes to determine dew formation from atmospheric vapor in soils in semiarid regions. *Arab. J. Geosci.* **2016**, *9*. [[CrossRef](#)]
13. Meng, Y.; Wen, X.F. Characteristics of dew events in an arid artificial oasis cropland and a sub-humid cropland in China. *J. Arid Land* **2016**, *8*, 399–408. [[CrossRef](#)]
14. Liu, W.J.; Liu, W.Y.; Li, P.J.; Gao, L.; Shen, Y.X.; Wang, P.Y.; Zhang, Y.P.; Li, H.M. Using stable isotopes to determine sources of fog drip in a tropical seasonal rain forest of Xishuangbanna, SW China. *Agric. For. Meteorol.* **2007**, *143*, 80–91. [[CrossRef](#)]
15. Kim, K.; Lee, X.H. Transition of stable isotope ratios of leaf surface moisture under simulated dew formation. *Plant Cell Environ.* **2011**, *34*, 1790–1801. [[CrossRef](#)]
16. Welp, L.R.; Lee, X.H.; Kim, K.; Griffis, T.J.; Billmark, K.A.; Baker, J.M. $\delta^{18}\text{O}$ of water vapour, evapotranspiration and the sites of leaf water evaporation in a soybean canopy. *Plant Cell Environ.* **2008**, *31*, 1214–1228. [[CrossRef](#)]
17. Xu, Y.Y.; Zhu, H.; Sun, X.J.; Meng, Q.L. A novel method for monitoring urban dew condensation and its application. *Tech. Gaz.* **2017**, *24*, 1509–1515.
18. Jia, Z.F.; Wang, Z.; Wang, H. Characteristics of dew formation in the semi-arid loess plateau of central Shaanxi Province, China. *Water* **2019**, *11*, 126. [[CrossRef](#)]
19. Jia, Z.F.; Zhao, Z.Q.; Zhang, Q.Y.; Wu, W.C. Dew yield and its influencing factors at the western edge of Gurbantunggut Desert, China. *Water* **2019**, *11*, 733. [[CrossRef](#)]
20. Nieto, R.; Gimeno, L.; Trigo, R.M. A Lagrangian identification of major sources of Sahel moisture. *Geophys. Res. Lett.* **2006**, *33*, L18707. [[CrossRef](#)]
21. Crawford, J.; Hughes, C.E.; Parkes, S.D. Is the isotopic composition of event based precipitation driven by moisture source or synoptic scale weather in the Sydney Basin, Australia? *J. Hydrol.* **2013**, *507*, 213–226. [[CrossRef](#)]
22. Ma, Q.; Zhang, M.J.; Wang, S.J.; Wang, Q.; Liu, W.L.; Li, F.; Chen, F.L. An investigation of moisture sources and secondary evaporation in Lanzhou, Northwest China. *Environ. Earth. Sci.* **2014**, *71*, 3375–3385. [[CrossRef](#)]
23. Xu, S.Q.; Liang, H.M.; Fu, S.A.; Hu, Y.X. Variation characteristics of evaporation in Jilin province from 1951 to 2015. *J. Meteorol. Environ.* **2018**, *34*, 71–77.
24. Bariac, T.; Rambal, S.; Jusserand, C.; Berger, A. Evaluating water fluxes of field-grown alfalfa from diurnal observations of natural isotope ecophysiological parameters. *Agric. For. Meteorol.* **1989**, *48*, 263–283. [[CrossRef](#)]
25. Dawson, T.E. Fog in the California redwood forest: Ecosystem inputs and use by plants. *Oecologia* **1998**, *117*, 478–485. [[CrossRef](#)]
26. Griffis, T.J.; Sargent, S.D.; Lee, X.; Baker, J.M.; Greene, J.; Erickson, M.; Zhang, X.; Billmark, K.; Schultz, N.; Xiao, W.; et al. Determining the oxygen isotope composition of evapotranspiration using eddy covariance. *Bound. Lay. Meteorol.* **2010**, *137*, 307–326. [[CrossRef](#)]
27. Xu, Y.Y.; Yan, B.X.; Luan, Z.Q.; Zhu, H.; Wang, L.X. Application of isotopic techniques in identifying the transformation among waters in the Sanjiang Plain. *Chin. Geogr. Sci.* **2013**, *23*, 435–444. [[CrossRef](#)]
28. Zhang, M.J.; Wang, S.J. A review of precipitation isotope studies in China: Basic pattern and hydrological process. *J. Geogr. Sci.* **2016**, *26*, 921–938. [[CrossRef](#)]
29. Sengupta, S.; Sarkar, A. Stable isotope evidence of dual (Arabian Sea and Bay of Bengal) vapour sources in monsoonal precipitation over North India. *Earth Planet. Sci. Lett.* **2006**, *250*, 511–521. [[CrossRef](#)]
30. Li, G.; Zhang, X.P.; Xu, Y.P.; Song, S.; Wang, Y.F.; Ji, J.M.; Xiang, J.; Yang, J. Characteristics of stable isotopes in precipitation and their moisture sources in Mengzi Region, Southern Yunnan. *Environ. Sci.* **2016**, *37*, 1313–1320.
31. Liu, J.R.; Song, X.F.; Yuan, G.F.; Sun, X.M.; Liu, X.; Wang, Z.M.; Wang, S.Q. Stable isotopes of summer monsoonal precipitation in southern China and the moisture sources evidence from $\delta^{18}\text{O}$ signature. *J. Geogr. Sci.* **2008**, *18*, 155–165. [[CrossRef](#)]
32. Peng, T.R.; Wang, C.H.; Huang, C.C.; Fei, L.Y.; Chen, C.T.A.; Hwong, J.L. Stable isotopic characteristic of Taiwan's precipitation: A case study of western Pacific monsoon region. *Earth Planet. Sci. Lett.* **2010**, *289*, 357–366. [[CrossRef](#)]
33. Wei, K.Q.; Lin, R.F. The influence of the monsoon climate on the isotopic composition of precipitation in China. *Geochimica* **1994**, *23*, 32–41.

34. Dansgaard, W. Stable isotopes in precipitation. *Tellus* **1964**, *4*, 436–468.
35. Wan, H.; Liu, W.G.; Xing, M. Isotopic composition of atmospheric precipitation and its tracing significance in the Laohequ Basin, Loess plateau, China. *Sci. Total Environ.* **2018**, *640–641*, 989–996. [[CrossRef](#)]
36. Zhang, S.C.; Sun, X.M.; Wang, J.L.; Yu, G.R.; Wen, X.F. Short-term variations of vapor isotope ratios reveal the influence of atmospheric processes. *J. Geogr. Sci.* **2011**, *21*, 401–416. [[CrossRef](#)]
37. Xing, M.; Liu, W.G. Short-term stable isotopic composition variations of near-surface atmospheric vapor vapor in four semiarid areas (Binxian, Guyuan, Wujiaochuan, Yuzhong) in interior northwestern China. *Environ. Earth Sci.* **2016**, *75*, 1272. [[CrossRef](#)]
38. Zhu, G.F.; Guo, H.W.; Qin, D.; Pan, H.X.; Zhang, Y.; Jia, W.X.; Ma, X.G. Contribution of recycled moisture to precipitation in the monsoon marginal zone: Estimate based on stable isotope data. *J. Hydrol.* **2019**, *569*, 423–435. [[CrossRef](#)]
39. Liu, W.J.; Li, P.J.; Li, H.M.; Duan, W.P. Estimation of evaporation rate from soil surface using stable isotopic composition of throughfall and stream water in a tropical seasonal rain forest in Xishuangbanna, China. *Acta Ecol. Sin.* **2006**, *26*, 1303–1311. [[CrossRef](#)]
40. Xu, Y.Y.; Yan, B.X.; Wang, L.X. Discrimination of vapour sources of dew in Sanjiang Plain by stable isotopic technique. *Environ. Sci.* **2011**, *32*, 1550–1556.
41. Luo, W.H.; Goudriaan, J. Dew formation on rice under varying durations of nocturnal radiative loss. *Agric. For. Meteorol.* **2000**, *104*, 303–313. [[CrossRef](#)]



© 2019 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (<http://creativecommons.org/licenses/by/4.0/>).