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Dew measurement and estimation of rain-fed jujube (*Zizyphus jujube* Mill) in a semi-arid loess hilly region of China

WANG Xing[1], GAO Zhiyong[2], WANG Youke[1,3*], Wang Zhi[4], JIN Shanshan[3]

[1] Institute of Soil and Water Conservation, Chinese Academy of Sciences and Ministry of Water Resources, Yangling 712100, China;
[2] Department of Water Conservancy, Yangling Vocational & Technological College, Yangling 712100, China;
[3] College of Water Resources and Architectural Engineering, Northwest A&F University, Yangling 712100, China;
[4] Department of Earth and Environmental Sciences, California State University, California 93740, USA

Abstract: Dew is an important water source for plants in arid and semi-arid regions. However, information on dew is scarce in such regions. In this study, we explored dew formation, amount, and duration of rain-fed jujube (*Zizyphus jujube* Mill) trees in a semi-arid loess hilly region of China (i.e., Mizhi County). The data included dew intensity and duration, relative humidity, temperature, and wind speed measured from 26 July to 23 October, 2012 and from 24 June to 17 October, 2013 using a micro-climate system (including dielectric leaf wetness sensors, VP-3 Relative Humidity/Temperature Sensor, High Resolution Rain Gauge, and Davis Cup Anemometer). The results show that atmospheric conditions of relative humidity of >78% and dew point temperature of 1°C–3°C are significantly favorable to dew formation. Compared with the rainfall, dew was characterized by high frequency, strong stability, and long duration. Furthermore, heavy dew accounted for a large proportion of the total amount. The empirical models (i.e., relative humidity model (RH model) and dew point depression model (DPD model)) for daily dew duration estimation performed well at 15-min intervals, with low errors ranging between 1.29 and 1.60 h, respectively. But it should be noted that the models should be calibrated firstly by determining the optimal thresholds of relatively humidity for RH model and dew point depression for DPD model. For rain-fed jujube trees in the semi-arid loess hilly regions of China, the optimal threshold of relative humidity was 78%, and the optimal upper and lower thresholds of dew point depression were 1°C and 5°C, respectively. The study further demonstrates that dew is an important water resource that cannot be ignored for rain-fed jujube trees and may affect water balance at regional scales.

Keyword: dew formation; dew amount; dew duration; jujube plantation; empirical models; Loess Plateau

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1 Introduction

In humid and semi-humid regions, precipitation is the main water sources, while dew only acts as a minor water source for plant growth (Jacobs and Nieveen, 1995; Kabela et al., 2009; Xu et al., 2012). However, in arid and semi-arid regions, dew is a crucially important water source (Malek et al., 1999; Li, 2002; Hao et al., 2012) and often the only water source for plants in some

*Corresponding author: WANG Youke (E-mail: gjzwyk@vip.sina.com)
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extremely dry regions (Kidron, 2000). Additionally, biological soil crusts, insects and small animals living in desert environments nearly completely depend on dew for their survival (Jacobs et al., 1999). For plants, moisture condensing on canopy surfaces can be directly absorbed by leaves as their supplementary water (Grammatikopoulos and Manetas, 1994; Liang et al., 2009; Zheng et al., 2011; Zhuang and Ratcliffe, 2012), thereby decreasing the vapour-pressure deficit and promoting the stomata opening and photosynthesis (Agam and Berliner, 2006), as well as affecting the actual canopy temperature (Bourque and Arp, 1994). As dew is a crucially important water source in arid and semi-arid regions, dew-related studies (e.g., dew formation, amount and duration) were previously conducted in these regions (Kidron et al., 2002; Zhuang and Zhao, 2010; Hao et al., 2012).

Previous studies on dew formation mainly focused on the chemical components, collection methods and field measurements (Ye et al., 2007), while scarcely involved on the development of estimation models. Due to the fact that the complexities and interactions of canopy structures with their surrounding environments, a large number of variables need to be considered in the estimation models (Dalla Marta et al., 2007; Sentelhas et al., 2007). Meanwhile, dew formation, as well as the amount, varies at regional scales and their influencing factors are still not well understood (Agam and Berliner, 2006; Limm and Dawson, 2010).

Dew duration is one of hot issues in dew studies (Agam and Berliner, 2006). There are two types of models that can be used to estimate dew duration effectively, including physical models and empirical models. Generally speaking, the physical models can accurately estimate dew duration, but too many input variables or parameters are needed in these models and some of the parameters are especially hard to obtain (Dalla Marta et al., 2007; Sentelhas et al., 2007, 2008; Li et al., 2010). In contrast, the empirical models can estimate dew duration using fewer and simpler input variables or parameters and sometimes the accuracy of the empirical models can be as good as that of the physical models (Rao et al., 1998; Kruit et al., 2004).

Chinese jujube (*Zizyphus jujube* Mill) is a traditional drought-resistant fruit tree. It is widely planted in the semi-arid loess hilly regions of China for over a thousand years. Due to excessive depletion of deep groundwater, soils in the semi-arid loess hilly regions of China are relatively dry and consequently natural vegetation in this region is characterized by stunted trees and grasses (Wang et al., 2010). Nevertheless, jujube can still be successfully cultivated on a plantation scale with exuberant green leaves (Liu et al., 2013), and there are currently about 1×10^6 hm^2 of planted jujube trees in the semi-arid loess hilly regions of China. Dew is a crucially important water source for the growth of jujube trees in the semi-arid loess hilly regions of China. However, information about dew on jujube trees in the semi-arid loess hilly regions of China is scarce (Li, 2002; Wang and Zhang, 2011).

Information on dew formation, amount and duration on jujube trees and, in particular, on rain-fed jujube trees in the semi-arid loess hilly regions of China, is essential to comprehensively understanding the ecological effect of dew in semi-arid regions. In this study, dew experiments were conducted in a semi-arid loess hilly region of China. The aims of this study were (1) to explore dew formation and its favourable forming conditions; (2) to determine dew amount; and (3) to accurately estimate dew duration of rain-fed jujube trees in this region by calibrating and verifying the empirical models. It is our hope that this study could provide scientific reference on dew information in the semi-arid loess hilly regions of China and also for other similar regions.

2 Materials and methods

2.1 Study area

The field experiment was conducted at the Mizhi Experimental Station of Northwest A&F University in the Chinese Loess Plateau (38°11'N, 109°28'E; 1049 m a.s.l.). The study area is characterized by a semi-arid temperate climate with mean annual precipitation of 451.6 mm and annual mean temperature of 8.4°C. It should be noted that most of the annual total precipitation occurs in the rainy season spanning from July to September. The annual sunshine duration and total radiation are 2761 h and 580.5 kJ/cm^2, respectively. Soil texture in the study area is loessial soil with mean soil bulk density (1.0-m depth) of 1.29 g/cm^3, field capacity of 23%, and gravimetric water content of 5.16%. Groundwater table in the study area is more than 50 m.

2.2 Experimental design and measurements

2.2.1 Experimental design

The experiment site was in a rain-fed jujube orchard with tree spacing of 2 m×3 m and total area of 4×10^3 m^2. Three 5-year jujube trees that grew uniformly (average height of 2 (±0.12) m) near the center of the orchard were selected as the objectives of dew measurements. It should be stated that the dielectric leaf wetness sensor developed by Decagon Devices Inc. was found to be suitable for on-site dew measurement (Sentelhas et al., 2004). Thus, the dielectric leaf wetness sensor was used in this study for dew measurements. We established a micro-climate system including the dielectric leaf wetness sensors, VP-3 Relative Humidity/Temperature Sensor, High Resolution Rain Gauge and Davis Cup Anemometer near the center of the orchard to conduct field measurements.

2.2.2 Measurements

Field measurements were conducted from 26 July to 23 October, 2012 and from 24 June to 17 October, 2013. Specifically, three dielectric leaf wetness sensors (Decagon Devices Inc., USA) were respectively set up at the canopy top of the three selected jujube trees to monitor dew intensity and dew duration (precisions of 0.01 mm and 1 min, respectively). Furthermore, relative humidity and temperature, rainfall, and wind speed were measured using an automatic weather station (Decagon Devices Inc., USA) installed 2.0 m above the ground surface. Relative humidity and temperature were measured using a VP-3 Relative Humidity/Temperature Sensor (precisions of 1% and 0.1℃, respectively), rainfall was measured using a High Resolution Rain Gauge (precision of 0.2 mm), and wind speed was measured using a Davis Cup Anemometer (precision of 0.1 m/s). All these sensors were connected to a single Em50 data logger and the data were automatically recorded at 15-min intervals. The leaf area index (LAI) of trees was measured every 10 days using the Winscanopy analysis equipment (Regent Instruments Inc., Canada).

2.3 Data processing

Based on field measurements, we established logistic functions of LAI with time in 2012 and 2013 using the Winscanopy 2005 software (Fig. 1).

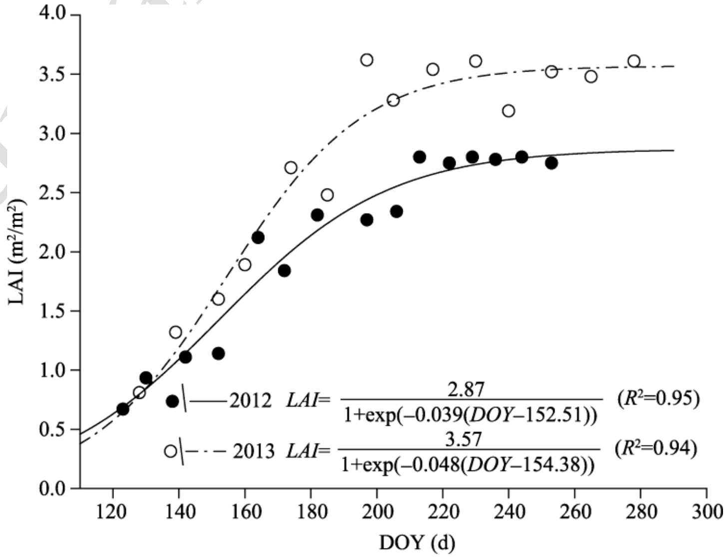

Fig. 1 Leaf area index (LAI) in 2012 and 2013. DOY, day of year.

In this study, the daily dew amount was defined as the maximum dew amount calculated from the highest dew intensity measured within a day (Zangvil, 1996). Dew amount at the i^{th} interval of time (W_{di}) was calculated as follows (Kabela et al., 2009; Xu et al., 2012):

$$W_{di} = I_i \times (2 \times LAI_i), \tag{1}$$

where, W_{di} is the dew amount at the i^{th} interval of time (mm); I_i is the dew intensity measured using the dielectric leaf wetness sensors at the i^{th} interval of time (mm); 2 represents the coefficient related to the upper and lower sides of the leaf; and LAI_i is the leaf area index measured at the i^{th} interval of time (m^2/m^2).

It is commonly accepted that leaf can acts as a reservoir because free water could accumulate on leaf surfaces through condensation. The capacity of leaf reservoir (W_{max}) was calculated by the following formula (Wilson et al., 1999):

$$W_{max} = 2 \times W_{leaf} \times LAI, \tag{2}$$

where, W_{leaf} is the maximum potential capacity of leaf reservoir storing free water per unit leaf area (mm; $W_{leaf} \leq 0.15$ mm).

Daily dew duration refers to the cumulative duration of all dew events (free water from the air condenses and stays on the leaf surfaces) within one day. It can be calculated as follows:

$$DD = \sum_{i=1}^{n} T_i, \tag{3}$$

where, DD is the measured daily dew duration (h); T_i is the measured duration of the i^{th} dew event (h); and n is the total number of dew events per day.

2.4 Estimation models of daily dew duration

2.4.1 Model description

We used the empirical models to estimate daily dew duration in this study and the following two empirical models were selected for daily dew duration estimation.

(1) Relative humidity model (RH model; Monteith, 1956): this model can conveniently estimate daily dew duration because relative humidity is the only parameter for estimation. Specifically, daily dew duration is equal to the number of hours with relative humidity greater than or equal to a specific threshold within a day.

(2) Dew point depression model (DPD model; Lawrence, 2005): in this model, dew point depression is the difference between air temperature and atmospheric dew point temperature (°C), which can be calculated using the Magnus-Tetens approximation method.

$$T_d = \frac{B_1\left(\ln\frac{RH}{100} + \frac{A_1 \times T}{B_1 + T}\right)}{A_1 - \left(\ln\frac{RH}{100} + \frac{A_1 \times T}{B_1 + T}\right)}, \tag{4}$$

where, T_d is the atmospheric dew point temperature (°C); RH is the relative humidity (%); T is the air temperature (°C); and B_1 and A_1 are constants, with the values of 243.04°C and 17.62, respectively.

The length of time that dew point depression remains between two critical temperatures of T_1 and T_2 (T_1<T_2) is regarded as the daily dew duration, where T_1 and T_2 are the threshold temperatures of wetness onset and dry-off (Gillespie et al., 1993).

2.4.2 Model calibration

The RH model and DPD model were calibrated through the following steps. First, the atmospheric dew point temperature was calculated using Equation 4. Second, the measured air temperature, relative humidity and dew duration combined with the calculated dew point depression (difference between air temperature and atmospheric dew point temperature) were employed to set up a database. Third, the initial thresholds of parameters in the RH model and DPD model were selected from previous studies (Rao et al., 1998; Kruit et al., 2004; Wang and Zhang, 2011) (Table 1). Fourth, each of the models was run at the step sizes of 1% in relative humidity and 0.1 ℃ in dew point depression to estimate daily dew duration. Fifth, the relationship between estimated daily dew durations and measured daily dew durations was established by calculating the coefficient of determination (R^2) using Equation 5. Sixth, steps (4) and (5) were repeated by changing the thresholds of parameters for the two models until the optimal thresholds appeared (corresponding to the highest R^2). The final optimal thresholds of parameters for the two models are shown in Table 1. Then, daily dew duration could be estimated using the two models with the final optimal thresholds. More detailed information about the model calibration can be found in Li et al. (2010).

$$R^2 = \left[\frac{\sum_{i=1}^{n}(O_i - \overline{O})(E_i - \overline{E})}{\sqrt{\sum_{i=1}^{n}(O_i - \overline{O})^2}\sqrt{\sum_{i=1}^{n}(E_i - \overline{E})^2}} \right]^2, \tag{5}$$

where, E_i is the estimated daily dew duration at the i^{th} day (h); $\overline{E}$ is the average of estimated daily dew durations (h); O_i is the measured daily dew duration at the i^{th} day (h); $\overline{O}$ is the average of measured daily dew durations (h); and n is the measurement days (n=55 d).

Table 1 Thresholds of parameters in the RH model and DPD model

Model	Parameter		Threshold	
			Initial	Final
RH model	Relative humidity (%)		80	78
DPD model	Dew point depression (℃)	Wet leaf	1.8	1.0
		Dry leaf	2.2	5.0

Note: RH model, relative humidity model; DPD model, dew point depression model. The initial thresholds were selected from the previous studies (Rao et al., 1998; Kruit et al., 2004; Wang and Zhang, 2011), while the final thresholds were determined from this study.

2.4.3 Model verification

The performances of the two empirical models (RH model and DPD model) were verified using the following indices: coefficient of determination (R^2), Willmott agreement index (W), confidence index (C), mean bias error (MBE) and mean absolute error (MAE) (Gao, 2004; Sentelhas et al., 2007).

$$W = 1 - \frac{\sum_{i=1}^{n}(E_i - O_i)^2}{\sum_{i=1}^{n}(|\overline{E_i}| - |\overline{O_i}|)^2}, \tag{6}$$

$$C = W\sqrt{R^2}, \tag{7}$$

$$MBE = \frac{\sum_{i=1}^{n}(E_i - O_i)}{n}, \tag{8}$$

$$MAE = \frac{\sum_{i=1}^{n}|E_i - O_i|}{n}, \tag{9}$$

where, E_i is the estimated daily dew duration at the i^{th} day (h); O_i is the measured daily dew duration at the i^{th} day (h); $\overline{E_i}$ is the mean deviation of estimated daily dew durations (h); $\overline{O_i}$ is the mean deviation of measured daily dew durations (h); and n is the measurement days (n=82 d).

2.5 Data analysis

In this study, all statistical analyses were performed using PASW Statistics 18.0 (SPSS Inc., Chicago, Illinois, USA). Significant differences of dew amounts versus the different meteorological factors at 15-min intervals were analyzed by Duncan's multiple comparison test at the 0.05 level. Furthermore, models were calibrated using R software (version 2.15.1), and all figures were plotted using Origin (version 2016).

3 Results

3.1 Dew formation and dew amount

In this study, we analyzed correlations between frequency of dew occurrence and main meteorological factors (including relative humidity, dew point depression, and wind speed) and between dew amount and main meteorological factors. It can be seen from Figure 2 that at 15-min intervals, dew formed (frequency of dew occurrence=5%) when relative humidity was in the range of 72%–78% and the cumulative frequency of dew occurrence reached up to 95% when the values of relative humidity were >78% (Fig. 2a). For dew amount, it differed significantly among different levels of relative humidity (P<0.05; Fig. 2d). The average dew amount was 0.31 mm when relative humidity was >90%, and was 0.11 mm when relative humidity was in the range of 72%–78%. These results demonstrated that relative humidity of 78% is an optimal threshold of relative humidity for dew formation, and dew will form more easily beyond the threshold.

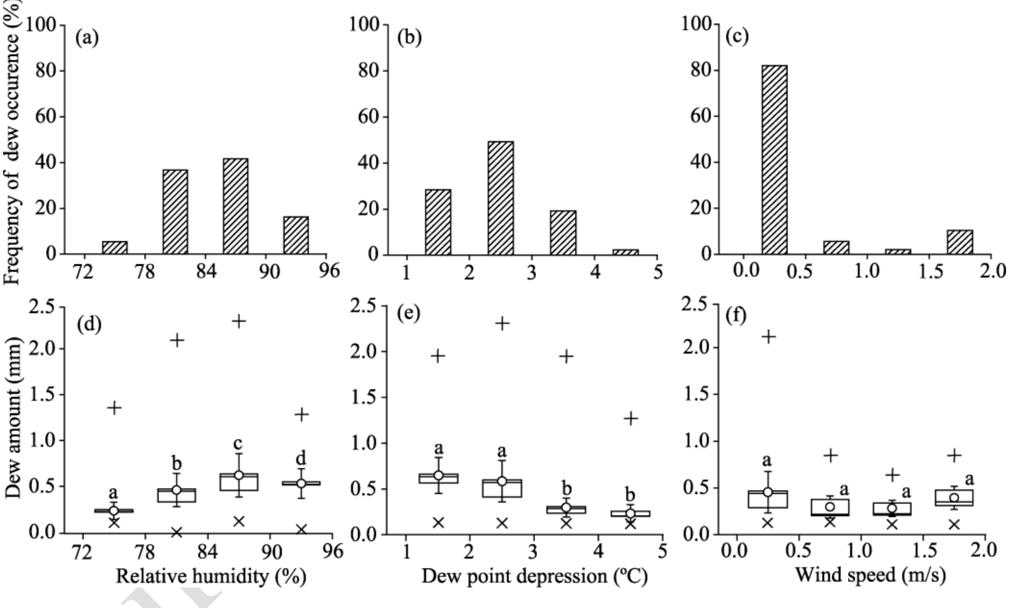

Fig. 2 Frequency of dew occurrence (a, b, c) and dew amount (d, e, f) under different meteorological factors at 15-min intervals from 26 July to 23 October, 2012 and from 24 June to 17 October, 2013. "○" represents the average daily dew amount"; "×" represents the minimum daily dew amount; "+" represents the maximum daily dew amount; bars represent the standard errors. Different lowercase letters indicate significant difference at the P<0.05 level (Duncan's multiple range test).

Figure 2b shows that the cumulative frequency of dew occurrence at 15-min intervals was 96% when dew point depression was in the range of 1℃–4℃ and was 50% when dew point depression was in the range of 2℃–3℃. For dew amount, no significant difference was observed between the dew point depressions of 1℃–2℃ and 2℃–3℃ (average dew amounts of 0.64 and 0.58 mm, respectively; P>0.05), while significant difference was observed between the dew point depressions of 3℃–4℃ and 4℃–5℃ (average dew amounts of 0.29 and 0.23 mm, respectively; P>0.05; Fig. 2e). Dew amount decreased with increasing dew point depression, especially after dew point depression reaching 3℃. The lowest value of dew amount at dew point depression of 3℃–5℃ was 0.23 mm, which was lower than the minimum average dew amount (0.35 mm) at dew point depression of 1℃–3℃. These results demonstrated that dew point depression of

1 ℃–3 ℃ was favourable for dew formation. Furthermore, frequency of dew occurrence was high (82%) when wind speed was <0.5 m/s (Fig. 2c), and there was no significant difference of dew amount among different wind speeds (P>0.05; Fig. 2f).

The daily dew amount, rainfall and relative dew frequency during the experimental periods (i.e., 26 July–23 October, 2012 and 24 June–17 October, 2013) are shown in Figure 3. The total dew amount was 83.03 mm during the whole experimental period, which was much lower than the total rainfall (638.2 mm). The daily dew amount differed without any regular patterns. There were a total of 108 days with dew fall, accounting for 52.43% of the total experimental days; and there were a total of 69 days with rainfall, accounting for 33.49% of the total experimental days (Fig. 3a). Although the total daily dew amount was much lower than the total rainfall, dew occurred more frequently than rainfall did. Moreover, the coefficient of variation of rainfall (150.2%) was higher than that of dew (70.3%), indicating that daily dew amount varied less than rainfall did. The daily dew amount ranged between 0.11 and 2.30 mm in the all dew-falling days (totally 108 days), with a daily average of 0.75 mm (Fig. 3a). Moreover, the days with daily dew amount >0.2 mm accounted for 85.18% of the 108 dew-falling days (Fig. 3b), and 73.15% of the 108 dew-falling days had dew fall that exceeded the capacity of leaf reservoir storing free water.

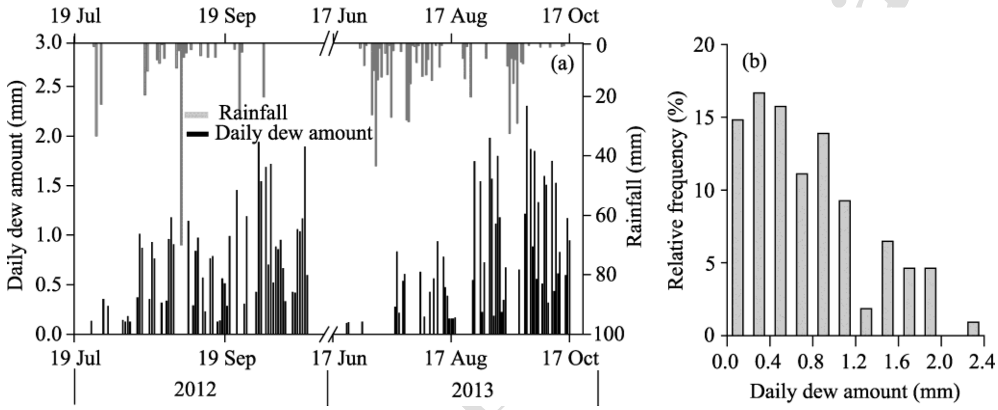

Fig. 3 (a) Daily dew amount and rainfall and (b) relationship between daily daw amount and relative dew frequency during the experimental periods (26 July–23 October, 2012 and 24 June–17 October, 2013)

3.2 Dew duration

In this study, the RH model and DPD model were used to estimate daily dew duration during the experimental periods. It should be noted that we run the model calibration firstly by determining the final optimal thresholds of parameters for the two models (relatively humidity for RH model and dew point depression for DPD model). The estimated daily dew durations were compared with the measured daily dew durations (Fig. 4). For the two models, the regression lines between estimated and measured daily dew durations were not significantly different from the 1:1 line, indicating that the estimated daily dew durations were as good as the measured durations. Furthermore, the performances of the two models are shown in Table 2, with R^2 values of 0.86 and 0.83 for RH model and DPD model, respectively. These results demonstrated that the final thresholds of relatively humidity (78%) and dew point depression (1.0 ℃ for wet leaf and 5.0 ℃ for dry leaf) determined in this study are acceptable to be respectively applied in RH model and DPD model for accurately estimating daily dew durations.

4 Discussion and conclusions

Water plays a vital role in the growth and development of plants. Generally speaking, plants evolve two effective strategies to uptake water, i.e., leaf water uptake strategy and root water uptake strategy (Ruiz-Sánchez et al., 2005). In the semi-arid loess regions of China, prolonged soil water deficiencies occur frequently and it is difficult for plants to absorb water by roots (Chen

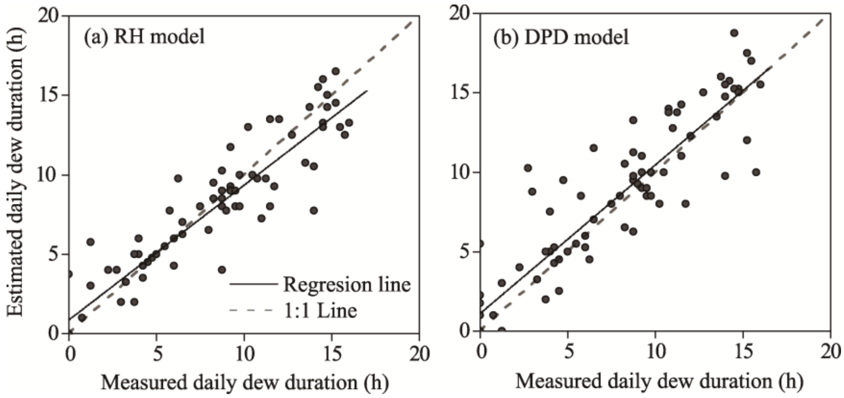

Fig. 4 Correlation of measured and estimated daily dew durations using RH model (a) and DPD model (b). RH model, relative humidity model; DPD model, dew point depression model.

Table 2 Indices of verifying the performances of RH model and DPD model

Model	R^2	*W*	*C*	*MAE* (h)	*MBE* (h)
RH model	0.86	0.96	0.89	1.29	–0.27
DPD model	0.83	0.95	0.86	1.60	0.73

Note: R^2, coefficient of determination; *W*, Willmott agreement index; *C*, confidence index; *MAE*, mean absolute error; *MBE*, mean bias error.

et al., 2005). Thus, leaf water uptake strategy is more important than root water uptake strategy. Plants can absorb water when water diffuses into their leaf surfaces via their leaf trichomes or hydathodes (Limm and Dawson, 2010), thereby increasing leaf relative water content and plant water status (Munné-Bosch et al., 1999). A study conducted on *Bassia dasyphylla* showed that leaf water uptake strategy increased shoot relative water content, promoted leaf photosynthate accumulation, and reduced shoot photosynthate distribution (Zhuang and Zhao, 2009). In addition, in the days with daily dew amount >0.2 mm, dew not only formed on the leaf surfaces but also dripped down to the soil surfaces, penetrating into the soil to supplement soil water loss by evaporation, affecting water balance at the soil–plant–atmosphere interface, and benefiting plant survival or growth (Ye and Peng, 2011).

Dew formation is affected by air water vapour distribution, water transportation and condensation-related environmental conditions (Ye et al., 2007; Zhang and Wang, 2007), and also by temperature and relative humidity (Beysens, 1995; Li, 2002; Xu et al., 2012). Temperature is a direct factor driving water vapour condensing process and relative humidity is an indirect factor influencing water vapour condensation (Wang and Zhang, 2011). Water vapour adsorption occurs when surface temperature is higher than atmospheric dew point temperature (Agam and Berliner, 2006). In the semi-arid loess regions of China, water vapour adsorption contributes more than 10% of the total water resource (Zhang et al., 2012).

Our study showed that dew formation was largely depended on relative humidity and dew point depression, and that the atmospheric conditions of relative humidity>78% and dew point depression of 1 ℃–3 ℃ were favourable for dew formation. Our results were inconsistent with the findings of Wang et al. (2010), who stated that the atmospheric conditions of relative humidity of >80% and dew point depression of –3 ℃–6 ℃ were favourable for dew formation. It was previously reported that wind speed of <0.5 m/s is beneficial to dew formation (Jackson and Moy, 1999; Wen et al., 2008). In this study, we also found that most of dew events occurred at wind speed <0.5 m/s. Light winds cool condensation surfaces and bring extra water vapour to the surfaces, thereby promoting dew formation (Zhang and Li, 2010). When winds weaken or diminish on the surfaces, water molecules diffuse to a stable zone and form small water drops, then water vapour gradients form, thereby increasing dew amount (Beysens, 1995). Muselli et al. (2009) reported that the threshold of wind speed to dew formation was 4.7 m/s in Zadar and 3.3–5.3 m/s in Komiža. Similarly, no dew events occurred at wind speed >2 m/s during the entire experimental periods in our study.

In this study, we calibrated and verified two empirical models (i.e., RH model and DPD model). After running model calibration (determining the final optimal thresholds of relatively humidity for RH model and dew point depression for DPD model), the models were then verified by comparing the estimated and measured daily dew durations and calculating the related statistic indices (R^2, W, C, MBE and MAE). In addition, the final threshold of relative humidity for RH model (78%; Table 1) agreed with the optimal threshold of relative humidity for dew formation (Fig. 2), confirming that relative humidity of 78% could be employed to judge whether dew formation occurs or not. The lower threshold of dew point depression for DPD model (1 ℃) agreed with the lower favourable value of dew point depression for dew formation, while the upper threshold of dew point depression for DPD model (5 ℃) was higher than the upper favourable value of dew point depression for dew formation (3 ℃). The difference could be explained by the processes of dew evaporation and condensation. Dew duration is the length of time that water is deposited by dew, involving evaporation process and condensation process. However, dew formation only involves the condensation process. From condensation to evaporation, dew point depression increases due to increased air temperature and decreased relative humidity. Consequently, the upper threshold of dew point depression for DPD model (5 ℃) was higher.

Some previous studies indicated that the threshold of relative humidity for RH model was 90% in humid regions (Madden et al., 1978; Sentelhas et al., 2008), being different from the result of our study (78%). In terms of the threshold of dew point depression for DPD model, different values were also obtained in different climate zones and also in different plant species (Madden et al., 1978; Rao et al., 1998; Sentelhas et al., 2008). The differences can be probably attributed to climate conditions and plant species. Specifically, dew formation depends on leaf temperature, which is determined by local climate conditions and plant characteristics. Therefore, the threshold can be used as a constant for the same plant species in the same regions, but it should be re-calibrated against for different climate zones and for different species.

To sum up, dew formation is a complex physical process, and atmospheric conditions of relative humidity of >78% and dew point depression of 1 ℃–3 ℃ are favourable for dew formation for the rain-fed jujube trees in the loess hilly regions of China. It should be particularly pointed out that the empirical models need to be calibrated and tested against local climate conditions and specific plant species before their applications.

Acknowledgements

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