Theoretical study on dew formation in plant canopies based on a one-layer energy-balance model

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Abstract

Dew formation on leaves plays an important role in plant growth and water use, but it also contributes to the development of a variety of plant diseases. However, the quantitative relationship between dew formation in plant canopies and meteorological conditions has not been fully elucidated. In the present study, a one-layer energy-balance model (1L-model) of a plant canopy was developed to systematically investigate this relationship, obtaining the following results: (1) Dew formation (condensation rate) on leaves is highly dependent on four parameters: effective radiation, relative humidity, air temperature, and exchange velocity (k_L) of the plant canopy. (2) Dew formation occurs when relative humidity (rh) exceeds the critical value (rh_{cr}), wherein rh_{cr} decreases with a decrease in effective radiation and is lower at lower air temperatures. (3) Under conditions where $rh > rh_{cr}$, the condensation rate reaches a maximum at a specific exchange velocity; however, condensation does not occur when k_L is greater than the critical value. (4) The maximum condensation rate increases with decreasing effective radiation, but rapidly decreases with decreasing relative humidity, and increases with increasing air temperature under humid conditions.

Given these theoretical considerations, we proposed two physical indices (reference dew amount, W_0, and potential dew amount, Wp) calculated from meteorological conditions using the 1L-model. Here, Wp is the maximum dew amount for given meteorological conditions, excluding wind speed. The efficacy of W_0 and Wp in assessing leaf wetness duration (LWD) and dew amount in plant canopies was confirmed through actual measurements in a rice paddy and numerical simulations using a more comprehensive multilayer energy-balance model.

This study contributes to a better understanding of the nature of dew formation on plants and improves the accuracy of LWD and dew amount estimation in plant canopies for the prevention of various plant diseases.

Keywords:

Leaf wetness, Micrometeorology, Potential dew amount, Reference dew amount, Rice paddy, Surface energy balance

Abbreviations:

1L-model, one-layer energy-balance model; LWD, leaf wetness duration; MLC-model, multilayer canopy energy-balance model

1. Introduction

Dew formation plays an important role in plant growth and water use (Limm et al., 2009; Dawson and Goldsmith, 2018; Berry, et al., 2019) and is a valuable water resource for plants in desert and arid regions (Agam and Berliner, 2006; Hill et al., 2015). Under humid weather conditions on clear nights, radiative cooling can decrease the temperature of leaves below the dew point, resulting in dew formation on leaf surfaces. To elucidate the ecological role of dew in plant communities, it is necessary to understand the mechanism of dew formation in plant canopies.

Conversely, dew formation is also widely known to provide favorable conditions for the development of a variety of plant diseases (Campbell and Madden, 1990; Magarey et al., 2005), such as rice blast and sheath blight of rice (Kobayashi et al., 2006; Katsantonis et al., 2017; Maruyama et al., 2023). Many studies have utilized leaf wetness duration (LWD) to predict the likelihood and severity of plant disease as the risk of infection for many plant diseases increases with LWD (Campbell and Madden, 1990; Huber and Gillespie, 1992). Given that farmers are increasingly implementing disease-warning systems, the need for easily accessible LWD data is growing (Rowlandson et al., 2015).

There are two known methods to evaluate LWD: measurement using condensation sensors and estimation using mathematical models, which are classified into physical and empirical models and utilize meteorological observation data as input values (Rowlandson et al., 2015). Physical models predict LWD based on the heat balance of the leaf surface (Pedro and Gillespie, 1981a, 1981b), and some models account for the wetting effects of rainfall (Papastamati et al., 2004; Magarey et al., 2006a, 2006b). In addition, the Penman–Monteith equation has been used to evaluate LWD (Montone et al., 2016). For example, Sentelhas (2006) evaluated LWD using a method derived from a crop evapotranspiration evaluation method which used the Penman–Monteith equation (Allen et al., 1998). Empirical models are also based on the physical process of condensation; however, they utilize statistical relationships between LWD and meteorological variables, such as relative humidity, dew point depression, air temperature, wind speed, and vapor pressure deficit (Gleason et al., 1994; Deshpande et al., 1995; Beruski et al., 2019; Zito et al., 2020). In recent years, empirical models for LWD estimation have also been developed using machine learning algorithms such as random forest, classification and regression tree, and neural network (Stella et al., 2017; Gao et al., 2020; Asadi and Tian, 2021; Shin et al., 2021).

Although many studies have provided practical solutions for predicting LWD, only a few of them have theoretically considered the properties of dew formation and its dependence on meteorological conditions (Monteith, 1957, 1961; Garratt and Segal, 1988). The energy budget for dew formation is explained in two leading textbooks on plant microclimate environments (Jones, 2013; Monteith and Unsworth, 2013); however, only a brief description is provided. In recent years, highly accurate real-time meteorological data that can be used to assess both LWD and dew amount have been produced locally and globally, including not only spatially dense data based on automated station networks but also gridded meteorological data based on ground-based observation networks and numerical weather forecasts (Rowlandson et al., 2015; Asadi and Tian, 2021). To effectively utilize these data, a theoretical understanding and organization regarding the characteristics and environmental dependence of dew formation based on canopy energy balance are needed. Such theoretical investigations are also essential for understanding the ecophysiological role of dew formation in plant survival and water use.

To address these issues, this study addressed two research objectives: (1) A theoretical examination of how dew formation is influenced by various meteorological factors by introducing a newly developed one-layer energy-balance model (1L-model) of a plant canopy, and, based on these theoretical examinations, (2) the proposal of two physical indices of dew amount (reference dew amount, W_0, and potential dew amount, Wp) calculated utilizing the 1L-model. Subsequently, the efficacy of W_0 and Wp in assessing LWD and dew amount was examined through actual measurements in a rice paddy field and numerical simulations using a more comprehensive multilayer energy-balance model. To our knowledge, this study provides the first theoretical framework for the physical characteristics of dew formation in plant canopies. The results presented here provide a physical basis for estimating not only LWD, but also dew amount in plant canopies.

2. Materials and Methods

2.1. One-layer energy-balance model (1L-model) of a plant canopy

2.1.1. Basic equations for evaluating dew formation in plant canopies

The heat budget for a one-layer plant canopy (Fig. 1) is given by the following equation:

$$R_{\mathrm{d}} + \sigma^* T_{\mathrm{S}}^4 = H_{\mathrm{L}} + lE_{\mathrm{L}} + 2\sigma^* T_{\mathrm{L}}^4, \quad (1)$$

$$R_{\mathrm{d}} \equiv (1 - r - \tau) S_{\mathrm{d}} + \varepsilon L_{\mathrm{d}}, \quad (2)$$

$$\sigma^* \equiv \varepsilon \sigma, \quad (3)$$

where R_d is the downward radiative flux, H_L is the sensible heat flux from the plant canopy, lE_L is the latent heat flux from the plant canopy (E_L is the rate of evaporation (kg m^{-2} s^{-1})), l is the specific latent heat of vaporization (J kg^{-1}), and T_L is the temperature of canopy leaves (canopy temperature; K). S_d is the solar radiation, and T_S is the equivalent blackbody temperature of the ground surface. The term L_d is the downward longwave radiation, r and τ are the shortwave reflectance (albedo) and transmittance of the plant canopy respectively, σ is the Stefan–Boltzmann constant (5.67×10^{-8} W m^{-2} K^{-4}), and ε is the emissivity of the plant canopy for longwave radiation (assumed to be 1.0 in this study). The units of each term in Eqs. (1) and (2) are W m^{-2}.

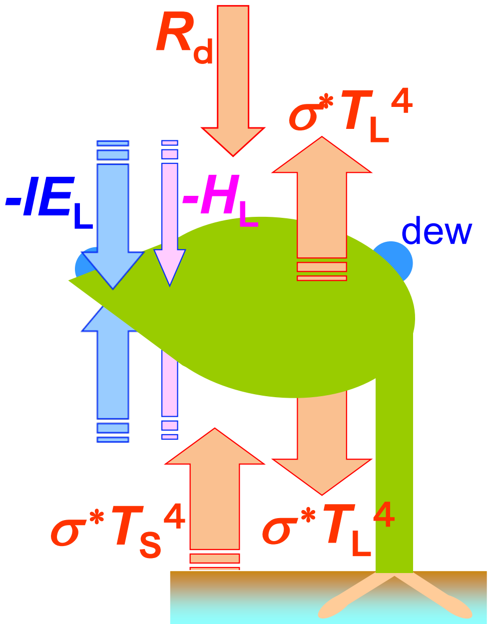


Figure 1. Illustration of the heat budget for a one-layer plant canopy (1L-model). Each term in the heat budget is explained in the first paragraph of Section 2.1.1. R_d: the downward radiative flux, H_L: the sensible heat flux, lE_L: the latent heat flux, T_L: the temperature of canopy leaves (canopy temperature), T_S: the equivalent blackbody temperature at the ground surface ($\sigma^* \equiv \varepsilon\sigma$; σ: the Stefan–Boltzmann constant, ε: the emissivity of the plant canopy for longwave radiation)

Sensible and latent heat fluxes were parameterized using bulk formulas (Kondo and Ishida, 1997; Kuwagata et al, 2008) as follows:

$$H_L = c_P \rho k_L (T_L - T), \tag{4}$$

$$lE_L = l\rho\beta k_L \{q_{SAT}(T_L) - rh\, q_{SAT}(T)\}. \tag{5}$$

where c_p is the specific heat of air at constant pressure (J kg^{-1} K^{-1}), ρ is the density of air (kg m^{-3}), T is the air temperature (K) just above the plant canopy, rh is the relative humidity just above the plant canopy, and $q_{SAT}(T_L)$ and $q_{SAT}(T)$ are the saturated specific humidity at the canopy temperature, T_L, and air temperature, T, respectively. The terms k_L and βk_L denote the exchange velocities for the sensible and latent heat fluxes (m s^{-1}), respectively, where β is the surface moisture availability.

Assuming $T_S = T_L$, Eq. (1) yields the following equation:

$$R_d - \sigma^* T^4 = H_L + lE_L + \sigma^*(T_L^4 - T^4). \tag{6}$$

Here, the assumption that $T_S = T_L$ is based on the fact that a larger percentage of dew accumulates in the upper part (upper layer) of the plant canopy (Jacobs et al., 1990; Wilson et al., 1999, Maruyama et al., 2023) and that the heat budget of this layer is only slightly affected by the ground surface temperature. Our numerical simulations of the dew formation in a rice canopy using a multilayer canopy energy-balance model suggested that the dew quantity of the entire plant canopy is not very sensitive to the ground surface temperature (paddy water temperature), which was recently reported by Maruyama et al. (2023). Equations (4)–(6) can be solved numerically for the three unknown variables (T_L, H_L, E_L), when the meteorological conditions (R_d - $\sigma^* T^4$, T, rh), k_L, and β are given. Here, effective radiation, R_d - $\sigma^* T^4$, is generally negative at night, and the nocturnal radiative cooling of the plant canopy increases with decreasing R_d - $\sigma^* T^4$.

Finally, dew formation (condensation rate), dW/dt, can be evaluated using the following equation:

$$dW/dt = -E_L/\rho_w, \tag{7}$$

where t is time (s), W is the dew amount on canopy leaves, expressed as the equivalent water depth above the ground surface (mm), and ρ_w is the density of water (10^3 kg m^{-3}).

We set β = 1.0 (assuming all leaves of the plant canopy are wet) and ε = 1.0 (assuming the plant canopy acts as a black body for longwave radiation) in this study. The former assumption is reasonable when dew is present. To calculate the saturated specific humidity in Eq. (5), the atmospheric pressure, p_s, was set as 1013 hPa.

The 1L-model is essentially similar to that of Kondo (1996). Equations (4)–(6) of the 1L-model are applied to plant canopies in this study; however, these equations are applicable to other objects, such as the surface of flat ground, single leaves, and microdroplets (Kondo, 1996). If the heat flux into the ground, G (positive downward), is not negligible relative to effective radiation, R_d - $\sigma^* T^4$, when evaluating dew formation on the flat ground surface, R_d - G should be used instead of R_d. As G generally depends on the ground surface temperature, an additional equation for G must be included in such a case.

2.1.2. Critical relative humidity and maximum possible condensation rate

Dew formation (condensation) occurs when T_L is lower than the dew point temperature, T_{dew} ($\leq T$). Under the condition of k_L = 0, no heat exchange occurs between the plant canopy and atmosphere; consequently, both H_L and lE_L (evaporation/condensation) fluxes are zero. During condensation, sensible and latent heat are transported from the atmosphere to the plant canopy (H_L, lE_L < 0); consequently, T_L increases from the k_L = 0 condition. Therefore, from Eq. (5), the necessary condition for condensation to occur in the plant canopy is derived as follows:

$$rh\, q_{\mathrm{SAT}}(T) > q_{\mathrm{SAT}}(T_{\mathrm{L00}}) \equiv rh_{\mathrm{cr}}\, q_{\mathrm{SAT}}(T), \quad (8)$$

where rh_{cr} is the critical value of relative humidity for condensation to occur and T_{L00} is the plant canopy temperature at $k_{\mathrm{L}} = 0$. By solving Eqs. (4)–(6) under the condition that $k_{\mathrm{L}} = 0$, T_{L00} can be expressed as follows:

$$T_{\mathrm{L00}} = \{(R_{\mathrm{d}} - \sigma^{*}T^{4})/\sigma^{*} + T^{4}\}^{1/4}. \quad (9)$$

Condensation does not occur when rh is less than rh_{cr}. Here, the value of rh_{cr} decreases with decreasing $R_{\mathrm{d}} - \sigma^{*}T^{4}$, as implied by Eqs. (8) and (9).

Moreover, the maximum possible value of the condensation rate for a given effective radiation and air temperature is obtained under the conditions of $rh = 1$ and $k_{\mathrm{L}} = \infty$. Solving Eqs. (4)–(6) for $rh = 1$ and $k_{\mathrm{L}} = \infty$ yields the following equation:

$$\mathrm{d}W/\mathrm{d}t\,|_{\mathrm{m}(rh=1)} = -\{(R_{\mathrm{d}} - \sigma^{*}T^{4})\mathit{\Delta}/(c_{\mathrm{P}} + l\mathit{\Delta})\}/\rho_{\mathrm{w}}, \quad (10)$$

where

$$\mathit{\Delta} \equiv \mathrm{d}q_{\mathrm{SAT}}/\mathrm{d}T. \quad (11)$$

Here, $\mathrm{d}W/\mathrm{d}t|_{\mathrm{m}(rh=1)}$ is defined as the "maximum possible condensation rate" in the present study. The same expression as Eq. (10) was derived by Monteith (1961).

2.1.3. Approximate solution

If we consider the condition that the difference between T and T_{L} is less than 5 °C ($|T_{\mathrm{L}}-T| <$ 5 °C), the approximation that $q_{\mathrm{SAT}}(T_{\mathrm{L}}) = q_{\mathrm{SAT}}(T) + \mathit{\Delta}(T_{\mathrm{L}}-T)$ and $T_{\mathrm{L}}^{4} - T^{4} = 4T^{3}(T_{\mathrm{L}} - T)$ can be made. With these approximations, the solution of Eqs. (4)–(6) for (T_{L}, H_{L}, E_{L}) is written as follows:

$$\hat{T}_{\mathrm{L}} - T = [(R_{\mathrm{d}} - \sigma^{*}T^{4}) - l\rho k_{L}\{(1-rh)q_{\mathrm{SAT}}(T)\}]/\{4\sigma^{*}T^{3} + \rho(c_{\mathrm{P}} + l\mathit{\Delta})\, k_{\mathrm{L}}\}, \quad (12)$$

$$\hat{H}_{\mathrm{L}} = c_{\mathrm{P}}\rho k_{\mathrm{L}}(\hat{T}_{\mathrm{L}} - T), \quad (13)$$

$$d\hat{W}/dt = -\hat{E}_{\mathrm{L}}/\rho_{\mathrm{w}} = -\rho k_{\mathrm{L}}\{(1-rh)q_{\mathrm{SAT}}(T) + \mathit{\Delta}(\hat{T}_{\mathrm{L}} - T)\}/\rho_{\mathrm{w}}, \quad (14)$$

where $\hat{X}$ (X: any variable) denotes values for the approximate solution.

2.1.4. *Physical parameters for the approximate solution*

In the approximate solution, the following seven physical parameters that characterize dew formation under given three meteorological conditions (R_d - $\sigma^* T^4$, T, rh) can be described analytically utilizing the following equations:

a. Maximum condensation rate (maximum dew formation):

$$d\widehat{W}/dt\,|_{\mathrm{m}} = (G_2/\rho_{\mathrm{w}})\left[G_1\{1 - 2(\hat{k}_{\mathrm{Lm}}/\hat{k}_{\mathrm{L0}})\} - \hat{k}_{\mathrm{Lm}}\right]/(1 + \hat{k}_{\mathrm{Lm}}/G_1), \tag{15}$$

b. Exchange velocity for $d\widehat{W}/dt\,|_{\mathrm{m}}$:

$$\hat{k}_{\mathrm{Lm}} = G_1\left\{\left(1 + \hat{k}_{\mathrm{L0}}/G_1\right)^{1/2} - 1\right\}, \tag{16}$$

c. Critical exchange velocity for dW/dt = 0:

$$\hat{k}_{\mathrm{L0}} = -[\Delta(R_{\mathrm{d}} - \sigma^* T^4)/\{(1 - rh)q_{\mathrm{SAT}}(T)\} + 4\sigma^* T^3]/(c_{\mathrm{P}}\rho), \tag{17}$$

where

$$G_1(T) \equiv 4\sigma^* T^3/\{\rho(c_{\mathrm{P}} + l\Delta)\}, \tag{18}$$

$$G_2(R_{\mathrm{d}} - \sigma^* T^4, rh, T) \equiv \rho\,\{\Delta(R_{\mathrm{d}} - \sigma^* T^4) + 4\sigma^* T^3(1 - rh)q_{\mathrm{SAT}}(T)\}/(4\sigma^* T^3),$$

$$= \hat{k}_{\mathrm{L0}} c_{\mathrm{P}} \rho^2\,(1 - rh)q_{\mathrm{SAT}}(T)/(4\sigma^* T^3). \tag{19}$$

No condensation occurs when $k_L > \hat{k}_{\mathrm{L0}}$.

d. Canopy temperature for $k_L = 0$:

$$\hat{T}_{\mathrm{L00}} = T + (R_{\mathrm{d}} - \sigma^* T^4)/(4\sigma^* T^3). \tag{20}$$

e. Canopy temperature for $k_L = \hat{k}_{\mathrm{Lm}}$:

$$\hat{T}_{\mathrm{Lm}} = T + \{(R_\mathrm{d} - \sigma^* T^4) - l\rho(1 - rh)q_{\mathrm{SAT}}(T)\}/\{4\sigma^* T^3 + \rho(c_\mathrm{P} + l\Delta)\,\hat{k}_{\mathrm{Lm}}\}. \quad (21)$$

f. Canopy temperature for $k_\mathrm{L} = \hat{k}_{\mathrm{L0}}$:

$$\hat{T}_{\mathrm{L0}} = T - (1 - rh)q_{\mathrm{SAT}}(T)/\Delta. \quad (22)$$

g. Canopy temperature for $k_\mathrm{L} = \infty$:

$$\hat{T}_{\mathrm{L}\infty} = T - (1 - rh)q_{\mathrm{SAT}}(T)/(c_\mathrm{P}/l + \Delta). \quad (23)$$

Equations (15)–(17) and (21)–(22) hold true when $\widehat{rh}_{\mathrm{cr}} < rh < 1$. Here, $\widehat{rh}_{\mathrm{cr}}$ is the value of rh_{cr} for the approximate solution:

$$\widehat{rh}_{\mathrm{cr}} = 1 + \Delta(R_\mathrm{d} - \sigma^* T^4)/\{4\sigma^* T^3 q_{\mathrm{SAT}}(T)\}. \quad (24)$$

2.2. Definitions of reference and potential dew amounts

Two physical indices of dew amount of the plant canopy were proposed, which were calculated from the 1L-model. The first index is reference dew amount, W_0, which is defined as the dew amount for the given meteorological conditions (R_d - $\sigma^* T^4$, T, rh, u). Here, the meteorological conditions include wind speed, u, to evaluate the exchange velocity, k_L. The second index is potential dew amount, $W\mathrm{p}$, which is defined as the maximum dew amount for the given meteorological conditions (R_d - $\sigma^* T^4$, T, rh). The remarkable feature of $W\mathrm{p}$, unlike W_0, is that it does not depend on the wind speed u.

The values of W_0 and $W\mathrm{p}$ are evaluated using the following equations:

$$W_0(t + \Delta t) = \max[0, W_0(t) + (\mathrm{d}W/\mathrm{d}t)\Delta t], \quad (25)$$

$$W\mathrm{p}(t + \Delta t) = \max[0, W\mathrm{p}(t) + (\mathrm{d}W/\mathrm{d}t|_\mathrm{m}^*)\Delta t], \quad (26)$$

$$\mathrm{d}W/\mathrm{d}t\,|_\mathrm{m}^* = \mathrm{d}W/\mathrm{d}t\,|_\mathrm{m} \qquad rh \geq rh_{\mathrm{cr}}, \quad (27\mathrm{a})$$

$$= \mathrm{d}W/\mathrm{d}t\ (k_\mathrm{L} = c_\mathrm{hL}u_\mathrm{min}) \qquad rh < rh_\mathrm{cr}, \tag{27b}$$

where t is time, Δt is the time interval for calculating W_0 and $W\mathrm{p}$, and $\mathrm{d}W/\mathrm{d}t$ and $\mathrm{d}W/\mathrm{d}t|_\mathrm{m}$ are the condensation rate (dependent on k_L) and the maximum condensation rate at $t = t + \Delta t/2$, respectively. Equation (27b) was used to set the minimum evaporation under conditions where no condensation occurred ($rh < rh_\mathrm{cr}$). In this study, Δt = 1800 s (= 30 min), u_min = 0.05 m s^{-1} (minimum wind speed), and c_hL = 0.05 (exchange coefficient) were adopted. During the daytime ($S_\mathrm{d} > 0$), r = 0.3 and τ = 0.2 (assuming paddy rice) were used in Eq. (2).

The exchange velocity, k_L, for calculating $\mathrm{d}W/\mathrm{d}t$ in Eq. (25) varies with the wind speed. Here, k_L was calculated from an empirical equation that considers the effects of both natural and forced convection (Watanabe and Mizutani, 1996) as in Maruyama et al. (2023). The typical length scale DL of the heat exchange object (the plant canopy; leaf aggregation) used in the equation for k_L depends on both the type of plant and the morphology of the plant canopy. In this study, DL = 0.1 m was used for the rice canopy for comparison with the measured data from irrigated rice paddy fields.

2.3. Measurement data in a rice paddy

To verify the efficacy of the two physical indices of plant dew quantity (W_0 and $W\mathrm{p}$) based on the 1L-model, we used dew amount data measured in a rice paddy field at the National Agriculture and Food Research Organization (NARO) Kyushu Okinawa Agricultural Research Center in Kumamoto Prefecture, Japan (32.8743°N, 130.7405°E, 76 m above sea level; Fig. 2) (Maruyama et al., 2023). The climate at the experimental site is warm temperate (humid subtropical climate), and the soil type is Andosol. The rice variety "Hinohikari" was transplanted on June 11, 2003 in a 500 m^2 plot (10 m × 50 m) with a spacing of 0.2 m × 0.3 m.

The dew amount in the rice canopy was measured at the center of the field on four nights — three nights during the booting period and one night during the grain-filling period.

The water depth in the field was maintained at approximately 5 cm during the dew observation period. During the booting and grain-filling period, air temperature, humidity, and wind speed were measured 2 m above the ground in the paddy field. A pyranometer and pyrgeometer were installed next to the paddy field to measure solar radiation and downward longwave radiation, respectively. Details of dew measurements and meteorological observations in the rice paddy fields are described by Maruyama et al. (2023).

In this study, the wind speed, u, for calculating k_L in the evaluation of W_0 was corrected by $u = u_{2m}\ln[(h - d)/z_0]/\ln[(z_{obs} - d)/z_0]$, where u_{2m} is the observed wind speed at z_{obs} (= 2 m) above the ground, h (= 1 m) is the height of the rice canopy, d (= 0.67h) is the zero-plane displacement, and z_0 (= 0.1 m) is the roughness length for momentum. The observed air temperature and humidity at 2 m above the ground were used without correction for the evaluation of W_0 and Wp.

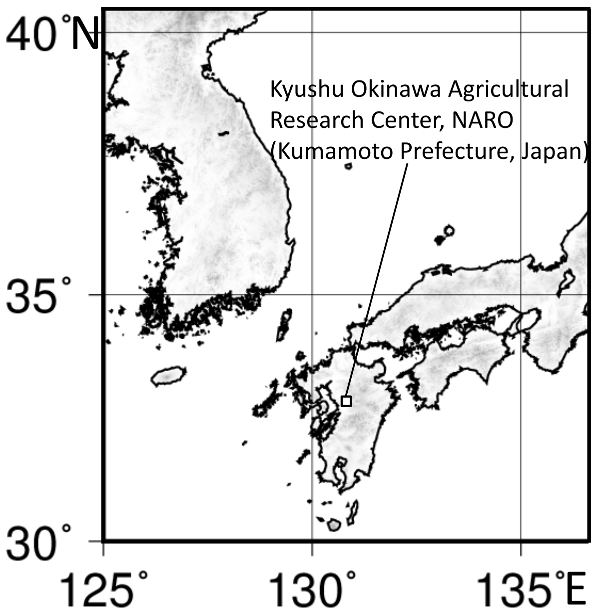


Figure 2. Location of the NARO Kyushu Okinawa Agricultural Research Center in Kumamoto Prefecture, Japan (32.8743°N, 130.7405°E, 76 m above sea level)

2.4. Simulation using a multilayer energy-balance model of a plant canopy

The LWD and dew amount estimated from the two physical indices, W_0 and Wp, were compared with those simulated using a multilayer energy-balance model of the plant canopy modified from the Multilayered Implementation for Natural Canopy-Environment Relations (MINCER; Watanabe et al., 2004, 2005). This modified model, the multilayer canopy energy-balance model (MLC-model) involves a one-dimensional, multilayer representation of the vertical transfer of momentum, heat, and water vapor in a plant canopy and calculates the vertical profiles of microclimates (such as air temperature and humidity, sensible and latent heat fluxes, and leaf temperature and dew amount) within and above the canopy by solving the leaf-scale energy budget and transfer equations throughout the canopy layer (Watanabe et al., 2004, 2005; Maruyama et al., 2023). Simulations using the MLC-model were conducted for the booting period (August 18–27, 2003) and the grain-filling period (September 24 to October 3, 2003). The simulation results were confirmed to be similar to the actual dew amount measurements from the rice paddy field (Maruyama et al., 2023). Details of the simulation using the MCL-model have been described by Maruyama et al. (2023).

3. Results

3.1. Simulation of dew formation based on 1L-model

3.1.1 Dependence of condensation rate on the exchange velocity and relative humidity

By solving Eqs. (4)–(6) of the 1L-model, we examined the dew formation characteristics under different meteorological conditions. Figure 3 shows the condensation rate, $\mathrm{d}W/\mathrm{d}t = - E_L/\rho_w$, and canopy-air temperature difference, $T_L - T$, as a function of exchange velocity, k_L (relative humidity: rh = 0.1–1.0, air temperature: T = 20 °C, effective radiation: $R_d - \sigma T^4 = - 50$ W m^{-2}, emissivity of the plant canopy: ε = 1.0). The dependence of $\mathrm{d}W/\mathrm{d}t$ on k_L and rh can be summarized as follows:

(1) At rh = 1.0 (100%), condensation rate increased with k_L.

(2) At $0.6 \leq rh < 1.0$, condensation rate reached a maximum value ($dW/dt|_m$) for specific k_L ($\equiv k_{Lm}$), and condensation transitioned to evaporation for larger k_L.

(3) At $rh < 0.6$, condensation did not occur, and evaporation occurred from wet leaf surfaces.

Because k_L increases nearly proportionately to wind speed, no condensation occurs in strong winds except when rh = 1.0.

Under the conditions of rh = 0.1–1.0, T = 20 °C, and $R_d - \sigma T^4 = -50$ W m^{-2}, $T_L - T$ is always negative, increasing with k_L for $rh > 0.3$ and decreasing with increasing k_L for $rh < 0.3$. When k_L approaches infinity, $T_L - T$ approaches $T_{L\infty} - T$ ($T_{L\infty} = T_{L\infty}(rh, T)$: function of rh and T). Here, $T_{L\infty}$ can be evaluated numerically by solving the following equation:

$$T_{L\infty} + (l/c_p)q_{SAT}(T_{L\infty}) = T + (l/c_p)rh\, q_{SAT}(T), \quad (28)$$

which is derived from Eqs. (4)–(6) by setting $k_L \rightarrow \infty$.

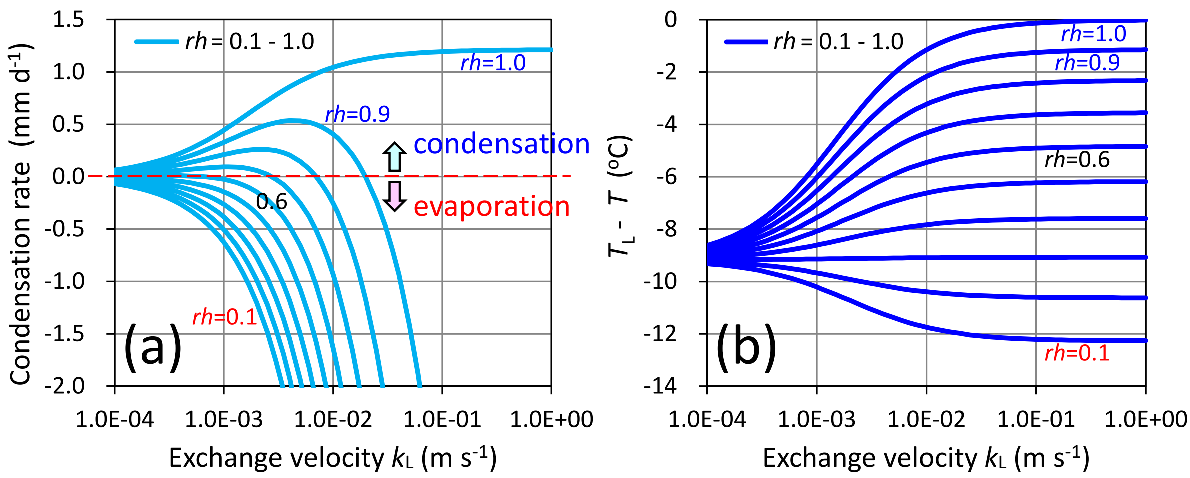


Figure 3. Dependence of (a) condensation rate, $dW/dt = -E_L$, and (b) canopy-air temperature difference, $T_L - T$, on the exchange velocity, k_L, based on the one-layer energy-balance model of the plant canopy (relative humidity: rh = 0.1–1.0 (10–100%), air temperature: T = 20 °C,

effective radiation: R_d - σT^4 = - 50 W m^{-2}, emissivity of the plant canopy: ε = 1.0). The same relationships for *rh* = 0.4–1.0 were also demonstrated in Kondo (1996).

3.1.2. Critical relative humidity for dew formation

Dew formation does not occur when *rh* is less than rh_{cr}. The value of rh_{cr} decreases rapidly with decreasing effective radiation and is somewhat lower at lower air temperatures (Fig. 4).

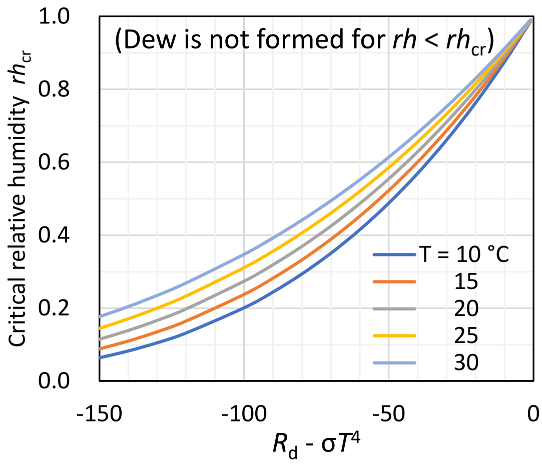


Figure 4. Dependence of the critical relative humidity, rh_{cr}, for dew formation on the effective radiation, R_d - σT^4, and air temperature, *T*. Dew formation does not occur when the relative humidity, *rh,* is less than the critical value, rh_{cr} (assuming the emissivity of the plant canopy, ε, is equal to 1.0).

3.1.3. Maximum condensation rate

The maximum condensation rate $dW/dt|_m$ depends strongly on both *rh* and R_d - σT^4 and varies with *T*; that is, under constant *rh* conditions, $dW/dt|_m$ increases linearly with decreasing R_d - σT^4, with the rate of increase being greater under higher air temperature conditions (Fig. 5). Under conditions of constant R_d - σT^4, $dW/dt|_m$ increases exponentially with *rh*, with the rate of increase being greater at higher air temperatures (Fig. 6). In contrast, $dW/dt|_m$ increases with increasing air temperature under humid conditions. However, when *rh* is close to rh_{cr}, $dW/dt|_m$ decreases with increasing air temperature (Figs. 5 and 6). Here, $dW/dt|_m$ for $rh = 1$ is analytically expressed using Eq. (10) (Section 2.1.2). Under the condition of $|T_{Lm} - T| < 5$ °C, $dW/dt|_m$ can be approximately expressed by Eq. (15) (Section 2.1.4).

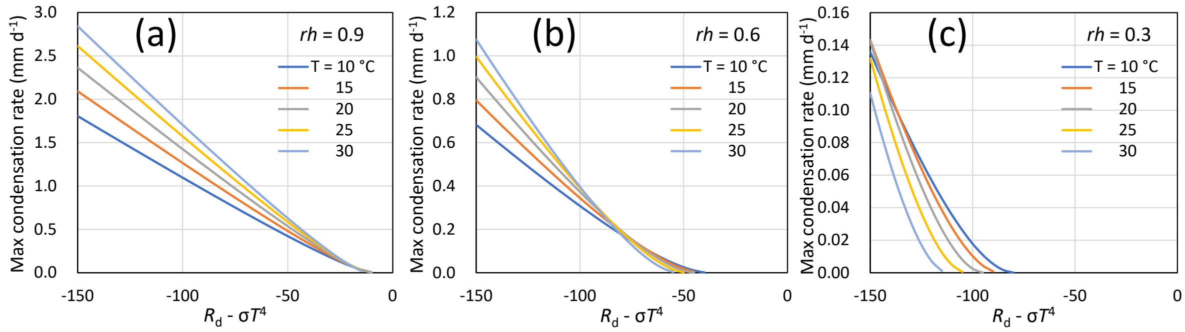


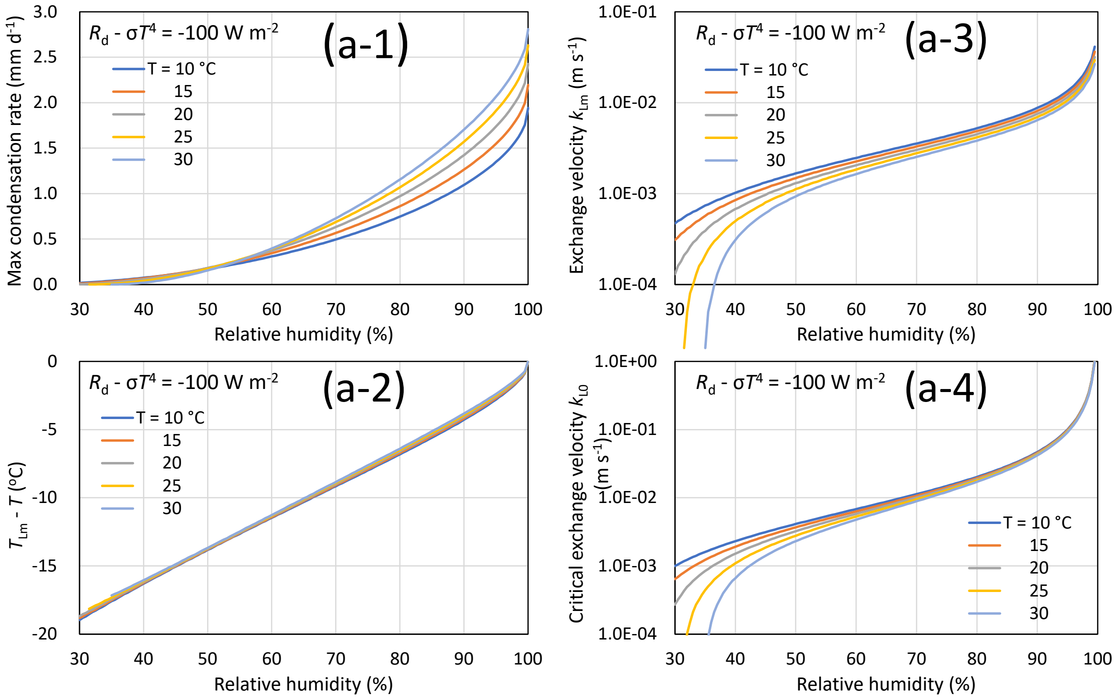
Figure 5. Dependence of maximum condensation rate, $dW/dt|_m$, on effective radiation, $R_d - \sigma T^4$, and temperature, T (for relative humidity: (a) $rh = 0.9$, (b) $rh = 0.6$, (c) $rh = 0.3$; emissivity of the plant canopy: $\varepsilon = 1.0$).

3.1.4. Exchange velocity for the maximum condensation rate and critical exchange velocity at which condensation transitions to evaporation

The exchange velocity, k_{Lm}, for maximum condensation and the critical exchange velocity, k_{L0} (at which condensation transitions to evaporation), are larger at higher relative humidity and increase with decreasing effective radiation, $R_d - \sigma T^4$ (Fig. 6). The dependence of k_{Lm} and k_{L0} on relative humidity and effective radiation can be understood by referring to the approximate solution under the condition of $|T_{Lm} - T| < 5$ °C (Eqs. (16) and (17) in Section 2.1.4). The value of k_L increases in approximate proportion to the wind speed; however, even under relatively strong wind conditions, high relative humidity and low effective radiation are likely to cause condensation.

3.1.5. Canopy–air temperature difference under the maximum condensation rate

The magnitude of the canopy–air temperature difference $|T_{Lm} - T|$ under the maximum condensation increases with decreasing effective radiation, $R_d - \sigma T^4$, and decreases with increasing relative humidity, *rh*; however, it is almost invariant with air temperature (Fig. 6). The approximate solutions (Eqs. (12)–(14) in Section 2.1.3) can be used if $|T_{Lm} - T|$ is less than 5 °C. When $R_d - \sigma T^4$ is equal to -100 W m^{-2}, $|T_{Lm} - T|$ is less than 5 °C only when *rh* is greater than 0.87 (Fig. 6a). Similarly, under the condition of $R_d - \sigma T^4$ = -50 W m^{-2}, $|T_{Lm} - T|$ is less than 5 °C only when *rh* is greater than 0.82 (Fig. 6b). In contrast, $|T_{Lm} - T|$ is always less than 5 °C under the condition of $R_d - \sigma T^4$ = -20 W m^{-2} (Fig. 6c). It also should be noted that the canopy temperatures T_L for the exchange velocities $k_L = 0$, k_{Lm}, k_{L0}, and ∞ are approximately expressed by Eqs. (20)–(23) (Section 2.1.4) under the condition that $|T_L - T|$ is less than 5 °C.



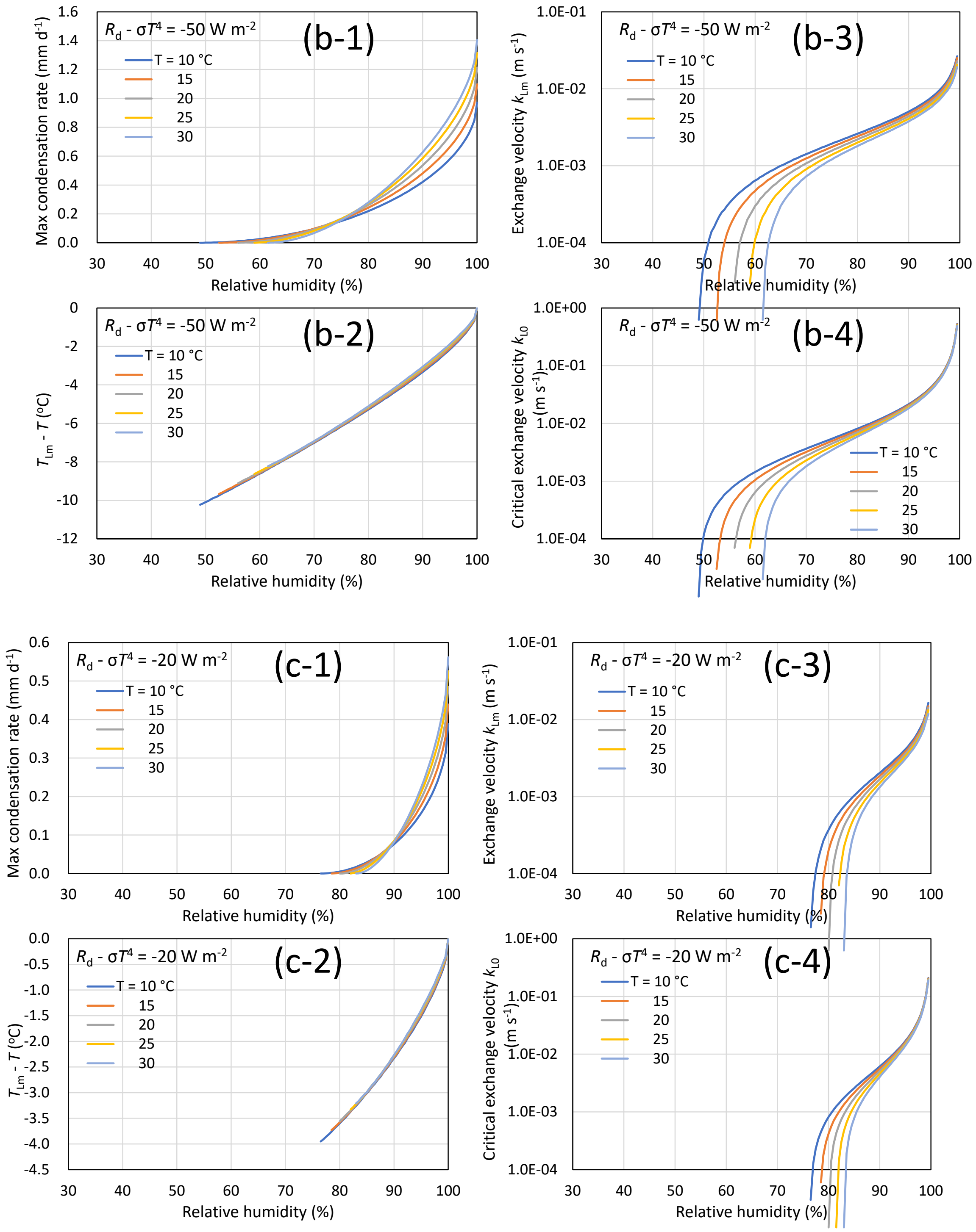


Figure 6. Maximum condensation rate, $dW/dt|_m$, canopy-air temperature difference, T_{Lm} - T, and exchange velocity, k_{Lm}, for maximum condensation, and critical exchange velocity, k_{L0}, for $dW/dt = 0$, as a function of relative humidity, *rh*, and air temperature, T (emissivity of the plant canopy: $\varepsilon = 1.0$). No condensation occurs under the condition $k_L > k_{L0}$. (a) effective radiation, $R_d - \sigma T^4 = -100$ W m^{-2}, (b) $R_d - \sigma T^4 = -50$ W m^{-2}, (c) $R_d - \sigma T^4 = -20$ W m^{-2}.

3.2. Intercomparison of the two physical indices, W_0 and Wp, measured data, and simulation with the MLC-model

In this section, the efficacy of the reference dew amount, W_0, and the potential dew amount, *W*p, in evaluating LWD and dew amount in a plant canopy is examined by comparison with the measured data in a rice paddy field and the numerical simulations using the MLC-model.

3.2.1. Time variations of the dew amount

As shown in Fig. 7, the MLC-model simulation predicted that a leaf dew amount of greater than 0.01 mm would form on eight nights between August 18 and 27, 2003 (booting period), and on all nights between September 24 and October 3, 2003 (grain-filling period). The measured dew amounts on the leaves were fairly consistent with those simulated by the MLC-model (Figs. 7 and 8a). The time variations in W_0 and *W*p also showed a similar trend as those of the dew amount simulated by the MLC-model, except that the values of *W*p were slightly larger than those simulated by the MLC-model (Fig. 7). The W_0 values were roughly consistent with those measured in the paddy fields (Fig. 8b), and the *W*p values were slightly larger than those measured (Fig. 8c).

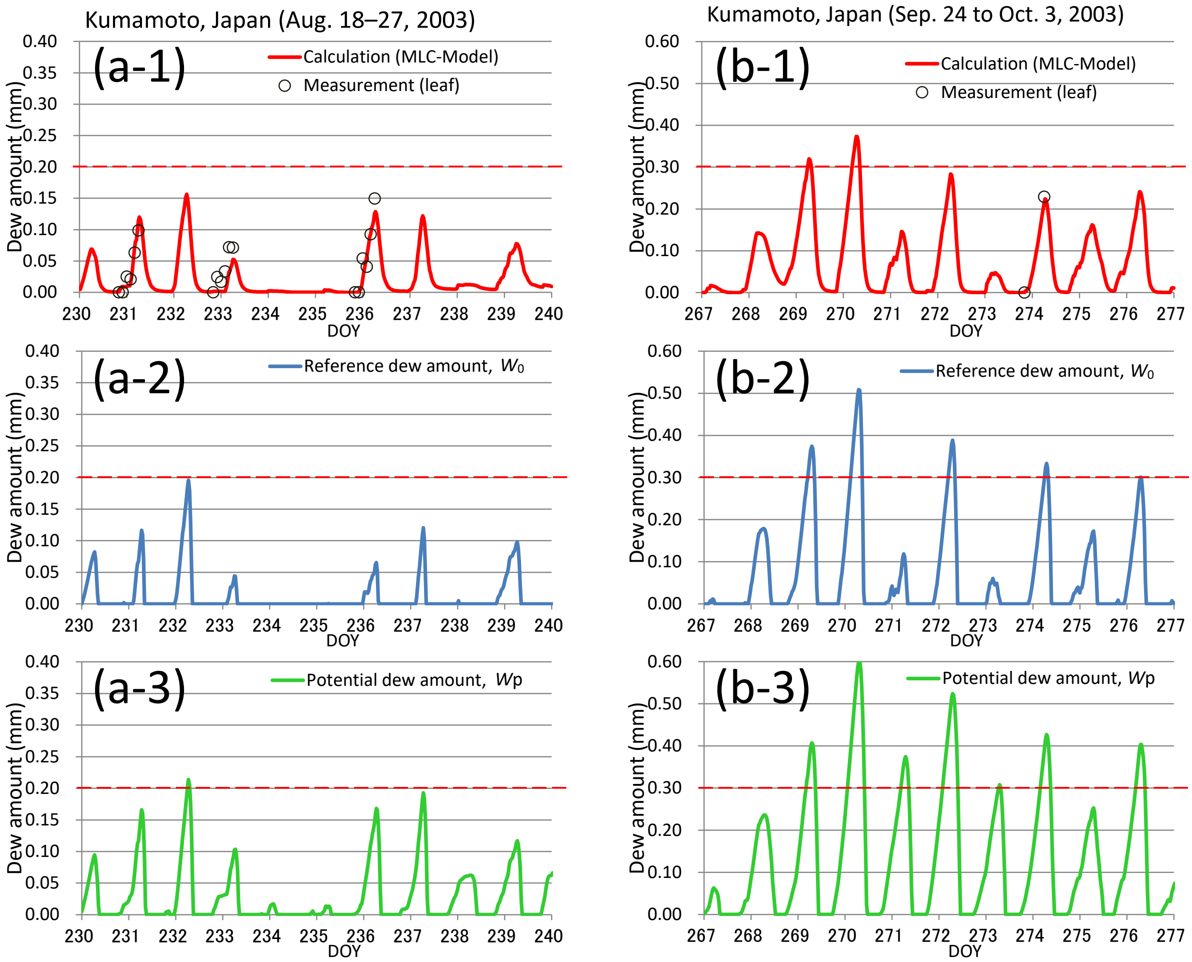


Figure 7. Time variations in the dew amount on leaves in the rice paddy field in Kumamoto, Japan. (a) August 18–27, 2003 (booting period, leaf area index (LAI) = 6.2); (b) September 24 to October 3, 2003 (grain-filling period, LAI = 3.7). There was no rain during either of these two periods. Calculations are based on the multilayer canopy energy-balance model (MLC-model) and measured data (top), reference dew amount, W_0 (middle), and potential dew amount, Wp (bottom). DOY: day of year

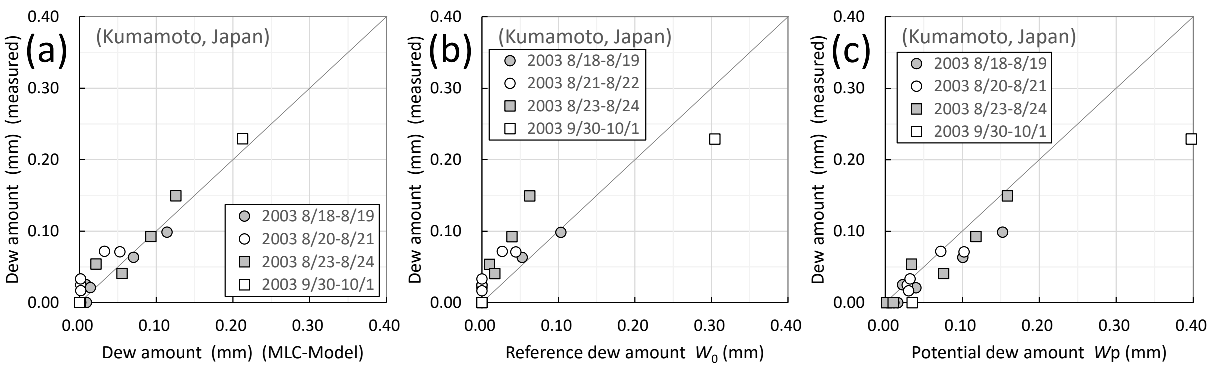


Figure 8. Comparison of the measured and simulated dew amounts on leaves in the rice paddy field. Vertical axis: measured dew amount. Horizontal axis: (a) dew amount calculated by the multilayer canopy energy-balance model (MLC-model), (b) reference dew amount W_0, and (c) potential dew amount Wp. The date is in a year month/day format.

3.2.2. Daily maximum of dew amount and leaf wetness duration

The MLC-model was confirmed to estimate the measured dew amount in the rice paddy fields with a high degree of accuracy (Figs. 7 and 8a). Therefore, to verify the efficacy of the two physical indices, W_0 and Wp, for the evaluation of dew formation, we compared the daily maximum dew amount and daily LWD based on W_0 and Wp with those simulated by the MLC-model (Figs. 8 and 9).

Visual observations during the observation period noted that dew on the leaf surface disappeared within approximately 1 h after sunrise. Thus, in this study, the daily LWD was defined as the duration that the dew amount was greater than 0.01 mm between the afternoon and 7:30 LT (local time) of the next day. If the minimum value of the dew amount W_{min} in the afternoon was greater than 0.01 mm for evaluating the daily LWD by the MLC-model, we assumed that the leaf wetness started when the dew amount exceeded W_{min} + 0.01 mm. This criterion was applied only for September 25–26 (W_{min} = 0.01 mm).

The results are summarized as follows:

(1) The daily maximum W_0 was approximately the same as that of the dew amount calculated using the MLC-model.

(2) The daily maximum Wp was slightly larger than that of the dew amount calculated using the MLC-model.

(3) The daily LWD based on W_0 was approximately the same as that calculated using the MLC-model.

(4) The daily LWD based on Wp was larger than that calculated using the MLC-model.

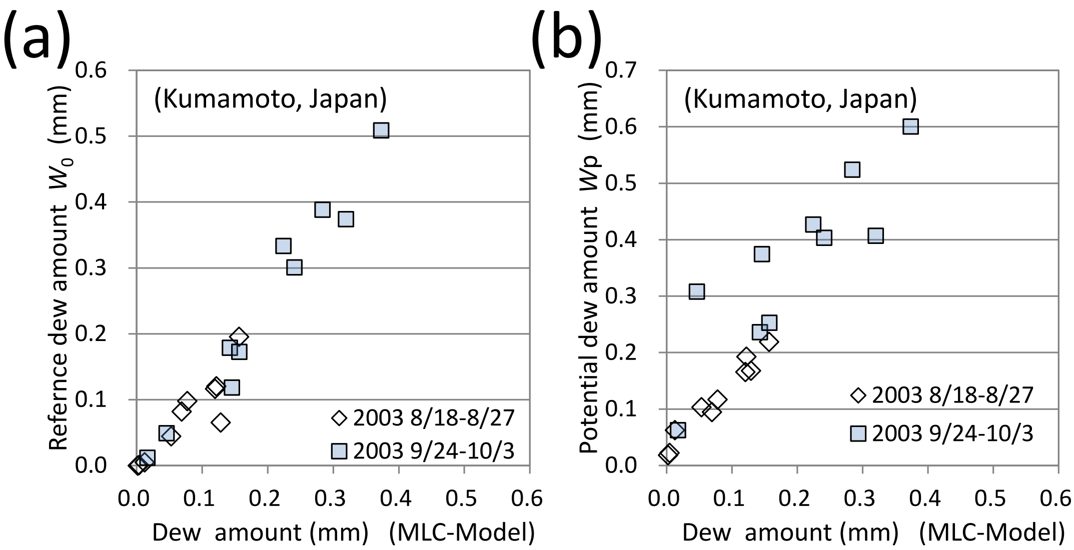


Figure 9. (a) Comparison between the daily maximum dew amount calculated by the multilayer canopy energy-balance model (MLC-model) and the daily maximum reference dew amount, W_0. (b) Same as Fig. 9a, except that the potential dew amount Wp was used instead of W_0. The date is in a year month/day format.

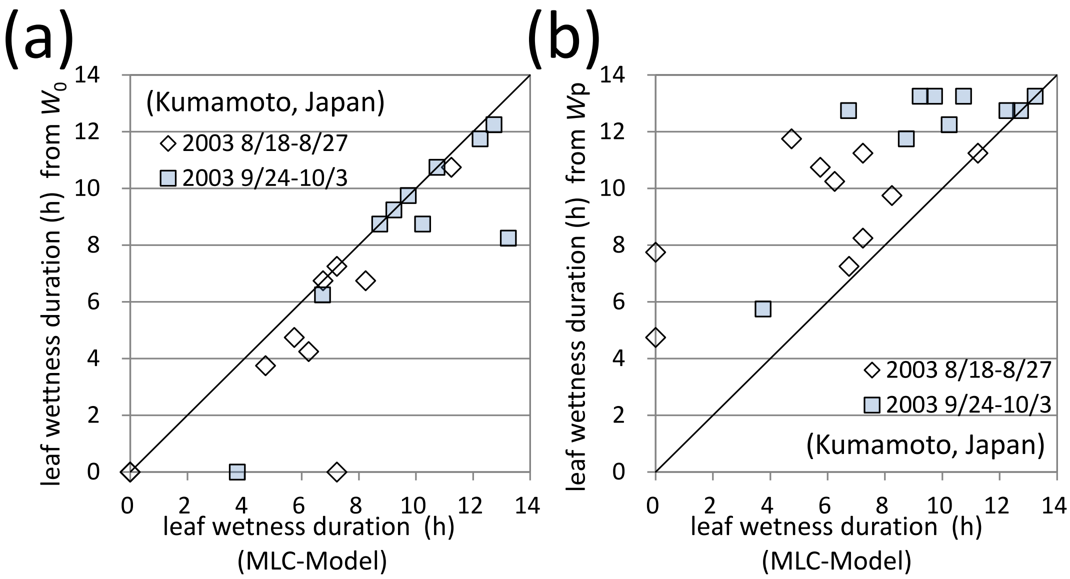


Figure 10. (a) Comparison between the daily leaf wetness duration (LWD) evaluated by the multilayer canopy energy-balance model (MLC-model) and the daily LWD based on the

reference dew amount W_0. (b) Same as Fig. 10a, except that the potential dew amount Wp was used instead of W_0. The date is in a year month/day format.

4. Discussion

4.1. Characteristics of dew formation based on the 1L-model

4.1.1. Dependence of dew formation on meteorological conditions

In this section, we further discuss the dependence of condensation rates on meteorological conditions implied by the proposed 1L-model. While it is intuitive that condensation is more likely to occur at higher relative humidity, as demonstrated by many previous studies (Sentelhas et al., 2008), we quantitatively demonstrate for the first time that condensation rate also strongly depends on effective radiation, air temperature, and exchange velocity in the plant canopy (Figs. 3, 5, and 6). As the exchange velocity increases with an increase in wind speed (Kondo, 1996; Watanabe and Mizutani, 1996), wind speed is an important meteorological parameter for dew formation. The exchange velocity also depends on plant type and plant canopy morphology (Section 2.1.5). The dependence of dew formation on meteorological conditions can be understood qualitatively by referring to an approximate analytical solution when the temperature difference between the canopy and air is less than 5 °C (Sections 2.1.3 and 2.1.4).

In most physical models (energy-balance models) for evaluating dew formation, net radiation, R_N (or $R_d - \sigma^* T_L^4$ in the case of the 1L-model) is used as an input variable instead of effective radiation, $R_d - \sigma^* T^4$ (Garratt and Segal, 1988; Papastamati et al., 2004; Magarey et al., 2006a; Sentelhas et al., 2006). However, R_N is not an independent meteorological parameter and depends on the plant canopy temperature, T_L. As T_L (and thus R_N) is determined as a result of the energy balance of the plant canopy (Section 2.1) and influenced by other meteorological conditions (Kuwagata et al., 2022), the use of R_N for the assessment of dew formation is inappropriate, especially for predictive purposes. Hereafter, effective radiation, R_d - $\sigma^* T^4$, should be used instead of R_N for an accurate estimation of dew formation.

4.1.2. Maximum condensation rate

The maximum possible condensation rate, $dW/dt|_{m(rh=1)}$, as derived by Monteith (1961), is only valid when the atmosphere is saturated ($rh = 1$) and k_L is sufficiently high (i.e., very strong wind speed). Theoretical considerations based on the 1L-model suggest that $dW/dt|_m$, under conditions where the atmosphere is unsaturated ($rh < 1$), is realized at a specific exchange velocity, k_{Lm}. The value of k_{Lm} increases with increasing relative humidity and decreasing effective radiation (Fig. 6). As shown in Section 3.1.3 (Figs. 5 and 6), $dW/dt|_m$ increases with increasing relative humidity and decreasing effective radiation. A positive correlation exists between $dW/dt|_m$ and air temperature under humid conditions but a negative correlation under relatively dry conditions.

4.1.3. Critical relative humidity for dew formation

In most empirical models for LWD prediction using relative humidity, the lower threshold of relative humidity for the occurrence of dew formation is set at around 0.9 (Sentelhas et al., 2008; Beruski et al., 2019). Our theoretical considerations based on the energy balance of a plant canopy clarified that the lower limit of the relative humidity required for dew formation (critical relative humidity, rh_{cr}) depends on both effective radiation and air temperature. Under conditions of low effective radiation (strong radiative cooling) and low air temperature, rh_{cr} is found to be theoretically much lower than 0.9 (Fig. 4); that is, for an effective radiation of < -100 W m^{-2}, condensation can occur even when rh is less than 0.4 ($rh_{cr} < 0.4$). However, the condensation rate decreases rapidly as rh decreases. For example, for an effective radiation of -100 W m^{-2} at 20 °C, the maximum condensation rate at $rh = 0.6$ is 26% (0.37 mm day^{-1}) of the value at rh = 0.9 (1.42 mm day^{-1}), and the maximum condensation rate at rh = 0.4 is only 4% (0.058 mm day^{-1}) (Fig. 6a). Furthermore, as rh decreases, the critical exchange velocity, k_{L0} (at which condensation transitions to evaporation), also decreases rapidly (Fig. 6); therefore, the range of exchange velocity (k_L = 0 to k_{L0}) at which condensation can occur becomes narrower with decreasing rh. Consequently, under conditions of lower relative humidity near rh_{cr}, there is a high possibility that once dew forms, it will be lost through evaporation.

4.1.4. Exchange velocity

Dew formation strongly depends on exchange velocity k_L. In the present study, the characteristics of condensation rate in the range of $k_L = 10^{-4}$ to 1 m s^{-1} are demonstrated (e.g., Fig. 3 in Section 3.1.1). The value of k_L in a plant canopy with a leaf area index greater than 0.5 is approximately 10^{-3} to 10^{-1} m s^{-1} (Watanabe, 1993; Kondo, 2000). As described in Section 2.1.1, the 1L-model is also applicable for estimating dew formation on arbitrary object surfaces such as a flat ground surface, single leaf, and microdroplet. Exchange velocity values of these objects are in the range of 10^{-4} to 10^{-2} m s^{-1} (flat ground surface), 10^{-2} to 10^{-1} m s^{-1} (single leaf), and 1 m s^{-1} (microdroplet) (Kondo, 1996).

4.2. Role of evaporation from the ground surface beneath a canopy in dew formation

Monteith (1957) proposed that there are two sources of leaf dew. The first source is the air above the canopy and is commonly called “dewfall.” The second source is evaporation from the ground surface beneath the canopy and is commonly called “distillation” or “dewrise.” In this study, total dew formation from these two sources is calculated using the heat budget equations (Eqs. (4)–(6)) for a one-layer plant canopy. From a micrometeorological point of view, evaporation from the ground surface beneath the canopy contributes to an increase in the relative humidity of the air just above and within the canopy, resulting in an increase in condensation on the leaves. Therefore, the condensation rate can be estimated with high accuracy from the heat budget of the plant canopy if the temperature and relative humidity of the air just above or within the plant canopy, in which the effect of distillation is reflected, are used as input meteorological conditions.

4.3. Efficacy of W_0 and Wp in evaluating LWD and dew amount in a plant canopy

In this study, we proposed two original physical indices of dew amount, W_0 and *W*p, based on the 1L-model. Here, *W*p was similar to the maximum possible condensation rate derived by Monteith (Monteith, 1961; Garratt and Segal, 1988), but the latter index cannot be used when the atmosphere is unsaturated ($rh < 1$). Although many models for evaluating dew formation in plant canopies have been proposed, the majority of them have been developed only for estimating LWD (Rowlandson et al., 2015). The advantage of utilizing W_0 and *W*p based on the 1L model is that these two physical indices can be used to estimate not only LWD, but also dew amount in plant canopies. The LWD and daily maximum dew amount in the rice plant canopy based on W_0 were consistent with those simulated by the MLC-model (Figs. 9a and 10a). This consistency indicates the usefulness of W_0 and *W*p for evaluating both LWD and dew amount in plant canopies, given that the MLC-model fairly accurately simulated the measured dew amount (Figs. 7 and 8a). The LWD and daily maximum dew amount in the rice plant canopy based on *W*p were slightly larger than those simulated by the MLC-model (Figs. 9b and 10b). These overestimations based on *W*p are likely because *W*p is the maximum dew amount possible under the given meteorological conditions (R_d - $\sigma^* T^4$, T, rh). As the actual W is also influenced by the wind speed through the change in k_L, W tends to be less than *W*p.

As discussed in Section 3.1, condensation rate is strongly influenced by effective radiation, relative humidity, air temperature, and k_L of the plant canopy. Of these four meteorological factors, rh is the most important. Therefore, precise measurements of rh just above the canopy are of the highest priority for an accurate estimation of LWD and dew amount, though an accurate estimation of effective radiation is important as well. Although we precisely measured downward longwave radiation, L_d, in our field observations, an empirical formula for L_d using other meteorological factors can be used (Kuwagata et al., 1990, 2011, 2022) when measurements of L_d are not available. The value of k_L increases with wind speed, and the horizontal heterogeneity of wind speed tends to be large under low wind conditions at night, resulting in an expected horizontal heterogeneity of dew amount on leaves. Considering these situations, it is preferable to use both physical indices, W_0 and Wp, to capture the horizontal distribution of LWD and the dew amount of plant canopies in actual agricultural fields.

In this study, the efficacy of two physical indices, W_0 and Wp, was confirmed using limited data for the evaluation of dew formation in rice paddy fields in Japan. Testing the practicality of W_0 and Wp in different regions and crops is left to future research. For some plant species in certain areas, wetting due to rainfall is also important for estimating LWD. We believe that incorporating the effect of wetting by rainfall into the physical indices of dew formation proposed in this study is straightforward.

4.4. Novelty and limitations of the study

To the best of our knowledge, the present study is the first comprehensive theoretical investigation of the physical characteristics of dew formation in plant canopies. The quantitative relationship between the condensation rate in plant canopies and various meteorological factors has not previously been elucidated to this degree. These results may be used not only to validate and improve many existing LWD estimation models, but also to develop the latest machine-learning-based models for estimating LWD and dew amount. The advancement of these models may help improve the accuracy of warning systems for various plant diseases, thereby improving disease prevention efforts. Furthermore, this study also serves as essential basic research for considering the ecological role of dew formation in plant canopies under various climatic conditions.

We used a simple one-layer energy-balance model to facilitate theoretical considerations of dew formation in plant canopies; however, this model cannot reproduce the vertical distribution of dew amount in a plant canopy, nor can it separate the total dew amount into dewfall and distillation. To address these issues, it is necessary to use a multilayer canopy energy-balance model such as the MCM-model (see Maruyama et al., 2023).

5. Conclusions

This study investigated how dew formation in a plant canopy is quantitatively influenced by several meteorological factors using the proposed 1L-model. Theoretical calculations using the 1L-model suggest that condensation rate is strongly dependent not only on relative humidity but also on other factors such as effective radiation, air temperature, and the exchange velocity of plant canopies. The lower limit of relative humidity at which dew formation occurs (critical relative humidity, rh_{cr}) depends on both effective radiation and air temperature. Under conditions of low effective radiation (< -100 W m^{-2}, strong radiative cooling) and low air temperature, rh_{cr} can be lower than 0.4; however, maximum condensation rate decreases rapidly with decreasing relative humidity. Furthermore, we proposed two physical indices for estimating the dew amount of plant canopies (reference dew amount, W_0, and potential dew amount, Wp), which were calculated using the 1L-model. Through the intercomparison of these two physical indices (W_0 and Wp), measured data, and simulations with the MLC-model, we confirmed that W_0 and Wp are effective not only for evaluating LWD but also for assessing dew amount in rice paddy fields. To the best of our knowledge, this study is the first to quantify the effects of multiple meteorological factors including effective radiation, air temperature, relative humidity, and exchange velocity of a plant canopy on dew formation (condensation rate) in plant canopies. We believe that these results will be extremely valuable for improving the accuracy of LWD and dew amount estimation in various plant species. Improved LWD estimation accuracy will also contribute to the prevention of various plant diseases through the improved accuracy of plant disease-warning systems.

Author contributions

TK designed the study and prepared the manuscript. JK and TK constructed the one-layer energy-balance model of a plant canopy and provided theoretical considerations. AM and TK conducted the field experiments. AM and TW conducted simulations using the multilayer canopy energy-balance model. All authors discussed the results and approved the manuscript.

Declaration of Competing Interests

The authors declare no conflicts of interest.

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Data Availability

Original data of the dew observation in the rice canopy used in this study are available at doi: 10.17632/fmvr43csy3.3.

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