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ARTICLE

# Predicting water surface evaporation in the paddy field by solving energy balance equation beneath the rice canopy

**Haofang Yan · Hiroki Oue · Chuan Zhang**

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**Abstract** The energy flux on the ground surface depends not only on climatological and biophysical controls in the vegetative canopy, but also on the available energy and energy partitioning beneath the canopy. Quantifying the evaporation and energy partitioning beneath the canopy is very important for improving water and energy utilization, especially in arid areas. In this study, we measured meteorological data, the net radiation and latent heat flux beneath the rice canopy, and then applied the radiation and energy balance equations to get the water surface temperature beneath the rice canopy. To apply the equations, we constructed shortwave and longwave radiation beneath the canopy sub-models and a bulk transfer coefficient sub-model. A plant inclination factor was parameterized with plant area index for the shortwave and longwave radiation sub-models. Bulk transfer coefficient was parameterized by plant area index and soil heat flux was predicted by the force restore model. With calculated water surface temperature and constructed sub-models, we reproduced net radiation and latent heat flux beneath the rice canopy. As a result, the reproduced water surface temperature, net radiation, and latent heat flux beneath the rice canopy were very close to the measured values and no significant differences were found according to 2-tail *t* test statistical analysis. Therefore, we conclude that these constructed sub-models could successfully represent water surface temperature, net radiation, and latent heat flux beneath the rice canopy.

**Keywords** Net radiation beneath the canopy · Plant-area index · Shortwave and longwave radiation · Water surface temperature and latent heat flux beneath the canopy

H. Yan (✉) · H. Oue · C. Zhang
United Graduate School of Agricultural Sciences, Ehime University, 3-5-7 Tarumi, Matsuyama 790-8566, Japan
e-mail: yanhaofang@yahoo.com

H. Oue
e-mail: oue@agr.ehime-u.ac.jp

C. Zhang
e-mail: zhangchuan010@163.com

## Introduction

The energy flux on the ground surface not only depends on climatological and biophysical controls in the vegetative canopy, but also on the available energy and energy partitioning beneath the canopy (Wilson et al. 2000). The energy balance has been studied extensively for different purposes (Oue 2001; Harazono et al. 1998; Tsai et al. 2007; Tyagi et al. 2000; Campbell et al. 2001a, b; Yoshimoto et al. 2005). A number of models have been developed to simulate processes of surface energy flux (Sellers et al. 1986; Meyers and Paw 1987; Maruyama and Kuwagata 2010). However, most of this research concentrated on the energy balance above the canopy. There has been little study of energy partitioning and consumption through evaporation beneath the canopy. It is well known that water consumption of the soil beneath the canopy is invalid and accounts for a large part of irrigation water especially when canopy density is low or in wet soil conditions (e.g., rice paddy field). Quantifying the evaporation and energy absorption by the ground surface beneath the canopy is very important for improving water and energy utilization, especially in arid areas. Kondo and Watanabe (1992) applied a double source model to calculate the energy balance at the ground and canopy levels separately. Yan and Oue (2011) used a similar method to calculate evaporation and transpiration. However, more studies are required to predict the energy flux on the ground surface beneath the canopy. In this study, the energy and radiation balance equations were employed to predict the latent heat flux on the water surface beneath the canopy. In order to solve the equations, sub-models of longwave and shortwave radiation beneath the canopy were constructed; bulk transfer coefficient on the water surface was parameterized by plant area index and soil heat flux was predicted by force restore model. The predicted water surface temperature, net radiation, and latent heat flux beneath the rice canopy were compared with measured values.

## Materials and methods

### Field observation

The experiment was conducted in a paddy field located at the Ehime University Senior High School, Matsuyama, Japan (33°50′N, 132°47′E). Rice (*Oryza sativa* L.), cv. Akita-Komachi, which is one of the main cultivars in Japan, was used for the experiment. Rice plants were transplanted into the field on 28th May, 2010, with 25 cm spacing between the rows, and 20 cm spacing within a row, which translates to a planting density of 20 hills/m$^2$, and harvested on 27th Aug, 2010. The elements of the radiation balance, i.e., (1 − alb)SR and $L_d - L_u$ were measured with CNR-2 (Kipp & Zonen, Netherlands) at 2.5 m and thus the net radiation (Rn) was calculated. Here, SR is global solar radiation, alb is the albedo of the paddy field, $L_d$ is the downward long wave radiation from the atmosphere and $L_u$ is the upward long wave radiation from the paddy field. In addition, global solar radiation was measured at a height of 2 m with another sensor (Decagon, USA). Downward and upward longwave radiation beneath the rice canopy ($L_{dg}$ and $L_{ug}$) were measured with PRI-01 (Prede, Japan) sensors. Solar radiation beneath the canopy ($SR_g$) was measured with a line type pyranometer (PCM-200). Soil heat flux ($G$) was measured at a depth of 2 cm with HFT3 soil heat plate (Campbell, USA), and water surface temperature ($T_g$) and soil surface temperature ($T_s$) at 2 cm depth were measured with thermocouple sensors. Vertical profiles (0.5, 1.0, and 2.0 m) of air temperature ($T_a$) and relative humidity above the canopy were measured with HMP-45A psychrometers (Vaisala, Finland) equipped with handmade ventilation fans and mounted in PVC pipes. Wind speed was measured with 014A three-cup anemometer (MetOne, USA) at the same height as $T_a$. All the data were sampled every 10 s, averaged every 10 min and recorded by a CR23X data logger (Campbell, USA). Plant (include leaf and panicle) areas were measured by sampling 3 rice plants to calculate plant area index (PAI), and plant height (PH) was measured with 10 designated rice plants every 7 or 10 days.

Water surface evaporation beneath the rice canopy ($E_g$, mm day$^{-1}$) was measured by a lysimeter (20 cm width × 60 cm length × 30 cm depth), which was buried between the crop rows. The water depth within the lysimeter was kept almost similar to that in the paddy field. $E_g$ was obtained by measuring the decrease in water level in the lysimeter at 8:00 and 18:00 every day from 2nd Jun to 27th Aug, 2010. The water depth in the paddy field was measured everyday at the same time as $E_g$.

### Energy and radiation balance beneath the rice canopy

The energy balance equation beneath the rice canopy could be expressed as

$$\mathrm{Rn_g} = \mathrm{LE_g} + H_g + G + \Delta W \tag{1}$$

where $G$ is the soil heat flux and $\Delta W$ is heat storage within the water, $\mathrm{LE_g}$ and $H_g$ are latent and sensible heat flux, respectively, from the water surface beneath the rice canopy (W m$^{-2}$). They are expressed by (Kondo and Watanabe 1992)

$$\mathrm{LE_g} = L\rho C_{Hg} u_2 \beta_g \left[e_*(T_g) - e_a\right] \tag{2}$$

$$H_g = c_p \rho C_{Hg} u_2 (T_g - T_a) \tag{3}$$

where $c_p$ and $\rho$ are the specific heat (J kg$^{-1}$ K$^{-1}$) and density of the air (kg m$^{-3}$), respectively, $L$ the latent heat of evaporation (J kg$^{-1}$), $T_g$ the water surface temperature (°C), $e_*(T_g)$ the saturated vapor pressure at $T_g$ (hPa). Also, $u_2$, $T_a$ and $e_a$ are the mean wind speed at 2 m (m s$^{-1}$), mean air temperature (°C) and actual vapor pressure at $T_a$ (hPa), respectively. $\beta_g$ is the surface moisture availability, which in the case of the water surface, $\beta_g = 1$. $C_{Hg}$ is the bulk transfer coefficient for sensible and latent heat from the water surface beneath the rice canopy to the reference height (2 m), no dimension. It could be parameterized with PAI as described in "Parameterizing $C_{Hg}$" section.

The soil heat flux $G$ is expressed by the force restore model (Blackadar 1976; Stull 1988; Matsushima and Kondo 1995; Hirota and Fukumoto 2009)

$$G = \frac{cD_a}{2}\left[\frac{2\pi}{\tau_y}(T_s - T_{ym}) + \frac{dT_s}{dt}\right] \tag{4}$$

where $c$ is the volumetric heat capacity of the soil ($c = 2.0 \times 10^6$ J m$^{-3}$K$^{-1}$), $D_a$ is the damping depth for annual value ($D_a = 1.7$ m), it was decided by fitting the calculated $G$ to the measured value, the similar value was applied by Hirota and Fukumoto (2009). $\tau_y$ is the annual period (365 days), $T_s$ is the soil surface temperature (°C), $T_{ym}$ is the annual mean soil temperature ($T_{ym} = 14$°C) which remains relatively constant to a depth of several meters (Hirota et al. 1995; Hirota et al. 2002), and therefore $T_{ym}$ can be adopted for any depth up to several meters.

The heat storage $\Delta W$ is expressed as

$$\Delta W = c_w \rho_w d_w \frac{dT_w}{dt} \quad (5)$$

where $c_w$ is the special heat of water ($c_w = 4.18$ J kg$^{-1}$K$^{-1}$), $d_w$ is the depth of the water layer (m), $\rho_w$ is the density of water (kg m$^{-3}$), and $T_w$ is the water temperature (°C).

The net radiation absorbed by the water surface beneath the canopy $Rn_g$ consists of net shortwave radiation ($SR_g - \alpha SR_g$) and longwave radiation ($L_{dg} - L_{ug}$). It can be expressed as

$$Rn_g = SR_g - \alpha SR_g + L_{dg} - L_{ug} \quad (6)$$

where $\alpha$ is albedo of the water surface beneath the rice canopy. In this study, $\alpha = 0.10$ was applied based on the value recommended by Oue (2003). $SR_g$ is the shortwave radiation beneath the rice canopy (W m$^{-2}$); $L_{dg}$ and $L_{ug}$ are downward and upward longwave radiation beneath the canopy (W m$^{-2}$). Simulation of $SR_g$ and $L_{dg}$ is as discussed in "Parameterizing $SR_g$ and $L_{dg}$" section. $L_{ug}$ could be expressed by the Stefan–Boltzmann Law (e.g., Kimura and Kondo 1998) as

$$L_{ug} = \varepsilon_s \sigma (T_g + 273)^4 + (1 - \varepsilon_s) L_{dg} \quad (7)$$

where $\varepsilon_s$ is the emissivity of the paddy field and assumed as unity in this study, and $\sigma$ is the Stefan–Boltzmann constant ($5.67 \times 10^8$ W m$^{-2}$ K$^{-4}$).

Substituting Eq. 7 into Eq. 6, and Eqs. 2–6 into Eq. 1, the energy balance equation could be shown as

$$\begin{aligned} &SR_g - \alpha SR_g + L_{dg} - \varepsilon_s \sigma (T_g + 273)^4 - (1 - \varepsilon_s) L_{dg} \\ &\quad = c_p \rho C_{Hg} u_2 (T_g - T_a) + L \rho C_{Hg} u_2 \beta_g [e_*(T_g) - e_a] \\ &\quad + \frac{cD_a}{2}\left[\frac{2\pi}{\tau_y}(T_s - T_{ym}) + \frac{dT_s}{dt}\right] + c_w \rho_w d_w \frac{dT_w}{dt} \end{aligned} \quad (8)$$

## Results and discussion

### Variations in radiation and heat flux beneath the canopy

Figure 1 shows the observations of shortwave radiation above and beneath the rice canopy (SR and $SR_g$), downward longwave radiation above and beneath the rice canopy ($L_d$, and $L_{dg}$) and upward longwave radiation beneath the rice canopy ($L_{ug}$), latent and sensible heat flux beneath the rice canopy ($LE_g$ and $H_g$), the water surface temperature and air temperature ($T_g$ and $T_a$), the variation of PAI and plant height from 2 June to 26 Aug, 2010. All of the meteorological data were compiled based on the average from 8:00 to 18:00. The $LE_g$ was obtained basing on the lysimeter measurement of water surface evaporation beneath the rice canopy. The absence of data at the end of July was due to the power to the data logger being cut. As shown in Fig. 1, $SR_g$ was close to SR when PAI $\le 2$ and both fluctuated due to the influence of rain, while $SR_g$ decreased with an increase in PAI until the value of $SR_g < 100$ W m$^{-2}$ at the end of July and became stable. Variation in $L_{ug}$ was smaller than $L_d$, and $L_{dg}$. The value of $L_{dg}$ moderately increased with growth of the crop and was obviously larger than $L_d$ when PAI $> 2$ because of the increase of downward longwave radiation from the canopy. The variations in heat flux differed for $LE_g$ and $H_g$. $H_g$ was relatively constant within the range −200 to 100 W m$^{-2}$ while $LE_g$ decreased with an increase in the coverage of the water surface and mainly reflected the variation in $SR_g$. The value of $LE_g$ remained almost constant during the late growth stage. The variations in $T_g$ and $T_a$ were between 20 and 35°C. Throughout the growth period, $T_a$ moderately increased after the rice seedlings were transplanting while $T_g$ showed a larger fluctuation. Moreover, $T_g$ just after transplanting was about 7°C higher than $T_a$. This difference decreased with rice growth, and $T_g$ was almost equal to or lower than $T_a$ from heading to maturity. A similar pattern between $T_g$ and $T_a$ was observed in a paddy field in a previous study (Maruyama and Kuwagata, 2010). PAI increased after transplanting, and decreased after heading. The maximum values of PAI and plant height were recorded at the beginning of August (the 64th day after transplanting), and were 5.11 and 100 cm, respectively. The heading day of rice plants was 25th July. In this study, the reason that PAI was measured and applied instead of leaf area index is that the contribution of the panicle area should not be neglected in the study of energy partitioning to the water surface beneath the canopy (Oue et al. 2008).

### The relationship between $T_g$ and $T_w$

In this study, the water depth within the paddy field was shallow and most of the time $d_w = 0$. Therefore, a relationship between $T_g$ and $T_w$ was analyzed (Fig. 2) and $T_g$ was very close to $T_w$. According to the 2-tail $t$ test statistical analysis, there was no significant difference found between $T_g$ and $T_w$. Based on this result, an assumption that $T_g = T_s = T_w$ was made in order to solve Eq. 8. With this assumption $T_g$ could be calculated from Eq. 8 by iterative method with measured meteorological data and the constructed sub-models of other variables ($SR_g$, $L_{dg}$ and $C_{Hg}$).

### Parameterizing $SR_g$ and $L_{dg}$

$SR_g$ was expressed by the following equation:

$$SR_g = SR \exp(-F \mathrm{PAI}) \quad (9)$$

where $F$ has been originally called as the inclination factor of the plant ($0 \le F \le 1$, Ross 1975). But it should be called as the contribution rate of cutting off and emitting the radiation by the plant body (Oue 2001). Oue (2003) modeled the vertical profile of $F$ of the rice plants by applying the multi-

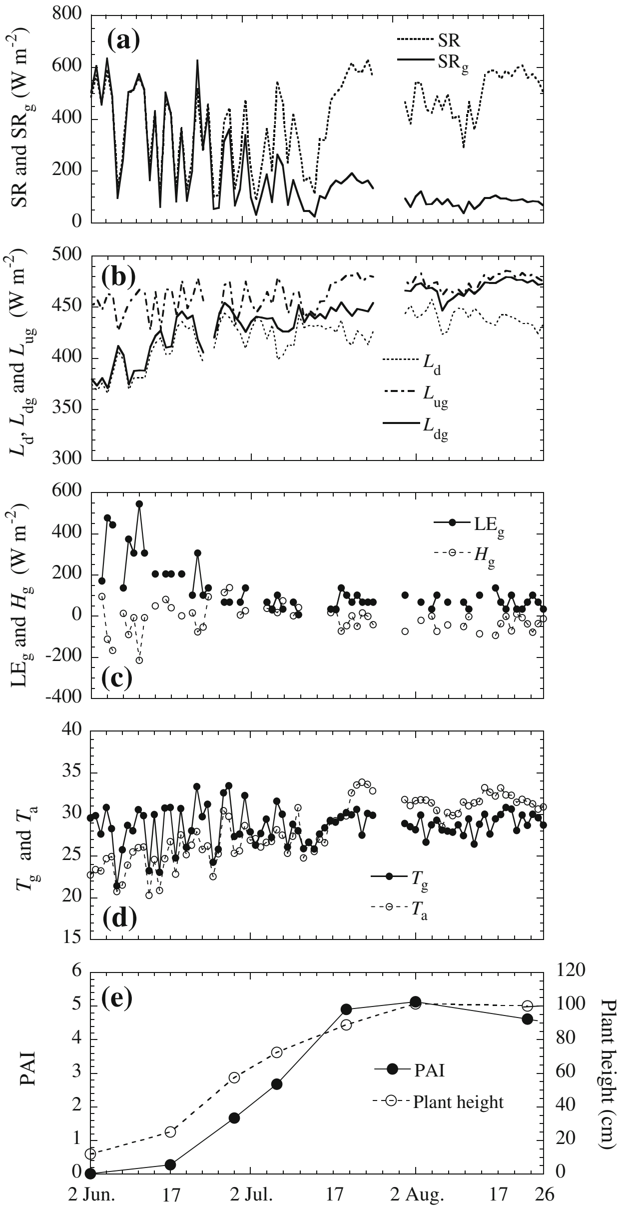


**Fig. 1** Seasonal variations in **a** solar radiation above and beneath the canopy (SR and SR$_g$), **b** longwave radiation above and beneath the canopy ($L_d$, $L_{dg}$ and $L_{ug}$), **c** latent and sensible heat flux beneath the rice canopy (LE$_g$ and $H_g$), **d** water surface temperature and air temperature ($T_g$ and $T_a$), **e** plant area index (PAI) and plant height, 2 June-26 Aug, 2010

layer model, and found that $F$ decrease with an increase in PAI. In this study, the value of $F$ was parameterized with PAI by dividing data into two stages (before and after heading). The relationship between PAI and $F$ (before and after heading) is shown in Fig. 3. The decrease in $F$ with the increase in PAI should be due to the increase of the leaves with the growth of plants. The separation and the increase after heading from before heading should be due to the leaning of leaves by the senescence. The regression equations are as Eqs. 10 and 11.

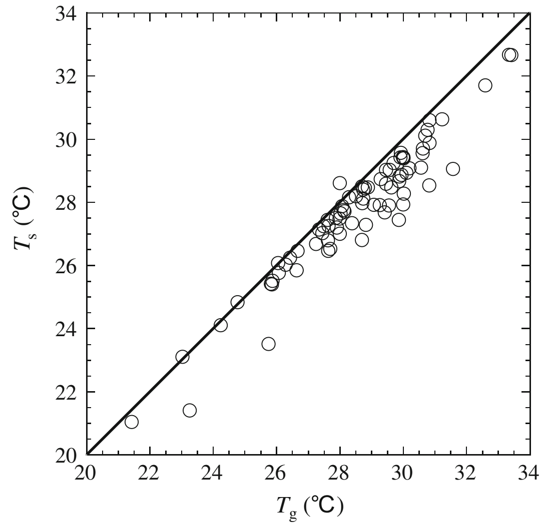


**Fig. 2** Comparison between $T_g$ and $T_s$

$$F = 1,\ \mathrm{PAI} \le 0.12$$
$$F = 0.57 - 0.47\log(\mathrm{PAI})\ \ 0.12 < \mathrm{PAI} < 5.11, \text{before heading} \tag{10}$$

$$F = 1.49 - 1.63\log(\mathrm{PAI}),\ \ 4.21 \le \mathrm{PAI} \le 5.11, \text{after heading} \tag{11}$$

Figure 4 shows the comparison between measured and reproduced SR$_g$. According to 2-tail $t$ test statistical analysis, there was no significant difference found between measured and reproduced SR$_g$.

$L_{dg}$ was expressed as Eq. 12

$$L_{dg} = (1 - F\mathrm{PAI})L_d + F\mathrm{PAI}\sigma(T_c + 273)^4 \tag{12}$$

where $\sigma$ is the Stefan–Boltzmann coefficient (W m$^{-2}$ K$^{-4}$). $T_c$ is the surface temperature of the bottom side of the plant body (°C). In this study, the parameter $F$ in Eq. 12 was assumed to equal to the $F$ in Eq. 9. Richard et al. (2008) employed a similar equation ($L_{dg} = vL_d + (1 - v)\ \sigma\ (T_c + 273)^4$) for modeling $L_{dg}$, where $v$ is the sky view factor ($v = 1 - F$ PAI in the current study). They parameterized $v$ by leaf area index with an exponential relationship. Verseghy et al. (1993) and Pomeroy et al. (2002) used a similar relationship for modeling sub-canopy longwave radiation for needle-leaf trees. As shown in Fig. 3, the $F$ which was parameterized by PAI was compared with their results by transforming $v$ to $F$, and the change in $F$ before heading in this study was close to their results.

Since $T_c$ in Eq. 12 is difficult to measure in the field, some researchers Richard et al. (2008) assume $T_c$ equal to air temperature within the forest canopy to simulate $L_{dg}$. However, significant error would be expected on a clear day due to shortwave heating. In this study, with $F$ value, $T_c$ could be calculated by $L_{dg}$, $L_d$ and PAI with Eq. 12. The

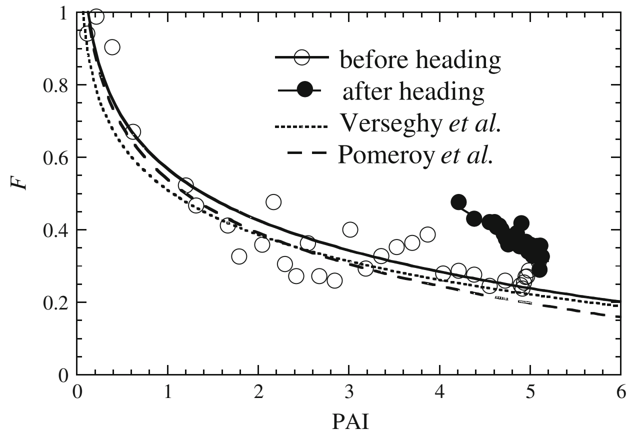


**Fig. 3** Relationship between PAI and $F$, *open* and *solid circles* are calculated $F$ from the observations of SR, SR and PAI before and after heading, respectively; the *solid line* is the regression line, *dashed* is given by the empirical relationship of Pomeroy et al. (2002) and Verseghy et al. (1993)

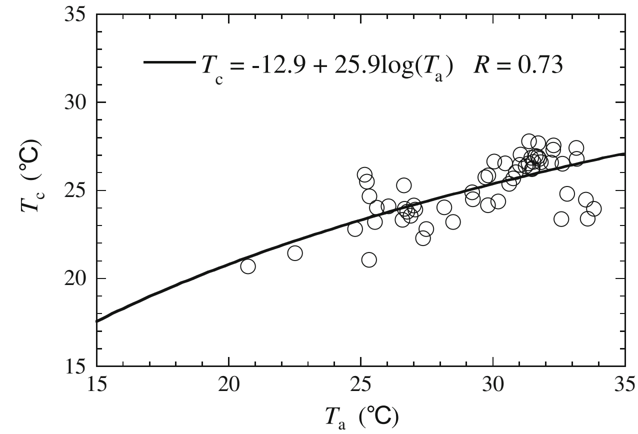


**Fig. 5** Relationship between $T_a$ and $T_c$

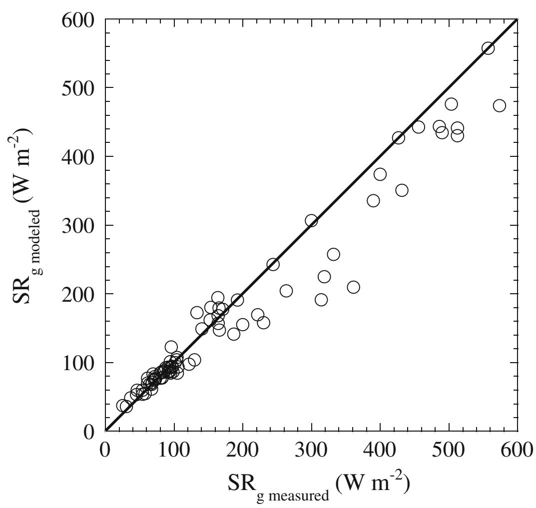


**Fig. 4** Comparison between measured and reproduced $SR_g$

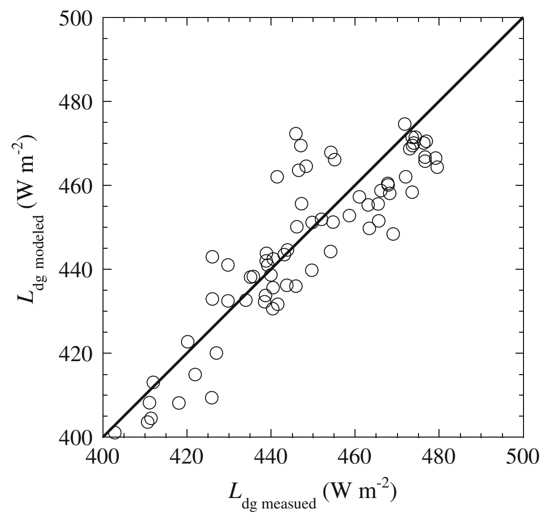


**Fig. 6** Comparison between measured and reproduced $L_{dg}$

relationship between air temperature at 2 m ($T_a$) and $T_c$ was shown in Fig. 5. Figure 6 shows the comparison between measured and reproduced $L_{dg}$. There was no significant difference found between measured and reproduced $L_{dg}$ according to 2-tail $t$ test statistical analysis.

## Parameterizing $C_{Hg}$

The bulk transfer coefficient can be estimated from the roughness length for momentum, roughness length for sensible heat, zero plane displacement, wind speed measurement, and universal function of the stability parameter (or Richardson number). However, the roughness length for sensible heat is not always easy to correctly estimate because the value is affected by the scale of fetch even under the same surface conditions (Hirota and Fukumoto 2009). The above method is complicated to calculate the bulk transfer coefficient from the water surface beneath the rice canopy to reference height (2 m) $C_{Hg}$. Until now, there has been limited research about $C_{Hg}$, especially the parametrization of $C_{Hg}$ based on actual measurements. In this study, $C_{Hg}$ was calculated by Eq. 2 with measured $LE_g$ and $T_g$ beneath the rice canopy. The relationship between PAI and $C_{Hg}$ was analyzed as shown in Fig. 7. There was a negative relationship between PAI and $C_{Hg}$. This result is consistent with Yan and Oue (2011) in which aerodynamic resistance from the water surface beneath the rice canopy to reference height ($r_{ag} = 1/(C_{Hg}u_2)$, s m$^{-1}$) decreased with an increase in PAI under the same wind speed conditions. Also, Kondo and Watanabe (1992) showed that $C_{Hg}$ decreased with an increase in leaf area density. The regression equation is as follows:

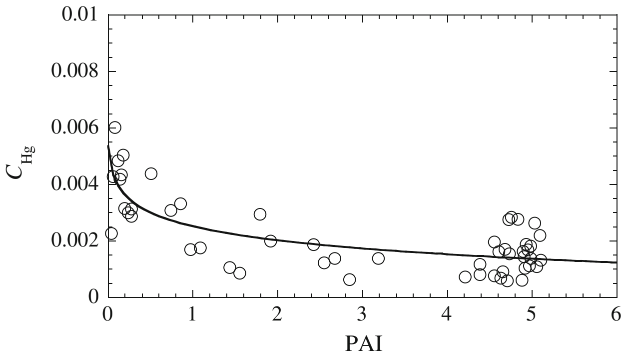


**Fig. 7** Relationship between PAI and $C_{Hg}$

$$C_{Hg} = -1.66 \times 10^{-3} \log(\text{PAI} + 0.019) + 2.53 \times 10^{-3} \tag{13}$$

## Reproduction of water surface temperature and latent heat flux beneath the rice canopy

The water surface temperature $T_g$ could be iteratively calculated by Eq. 8 with $SR_g$, $L_{dg}$, and $C_{Hg}$ sub-models and other meteorological data by applying the assumption which was mentioned in "The relationship between $T_g$ and $T_w$" section. Figure 8 shows the comparison between measured and modeled $T_g$. There was no significant difference between measured and modeled values according to 2-tail $t$ test statistical analysis. The correlation results were considered significant at $P < 0.05$. The average relative error between measured and modeled $T_g$ was around 2.1%, and the average absolute error was 0.49°C.

With modeled $T_g$, $Rn_g$ could be reproduced by substituting Eqs. 2 and 3 into Eq. 1. The result of comparing reproduced with measured $Rn_g$ is shown in Fig. 9. The average relative error between measured and reproduced $Rn_g$ was 12.3% and there was no significant difference between them according to 2-tail $t$ test statistical analysis.

$LE_g$ could be reproduced from Eq. 2 with calculated $T_g$ and parameterized $C_{Hg}$. The comparison between measured and modeled $LE_g$ (Fig. 10) shows most scatter data were distributed near 1:1 line. There was no significant difference between measured and reproduced $LE_g$ according to the 2-tail $t$ test statistical analysis. As a result, $SR_g$, $L_{dg}$, $C_{Hg}$ and $G$ sub-models which were constructed by actual measurements could be applied to predict the energy balance beneath the rice canopy. However, since the calibration was based on only one year's data, more studies are needed for next step.

## Conclusion

In this article, the energy balance method was applied to predict water surface evaporation beneath the rice canopy

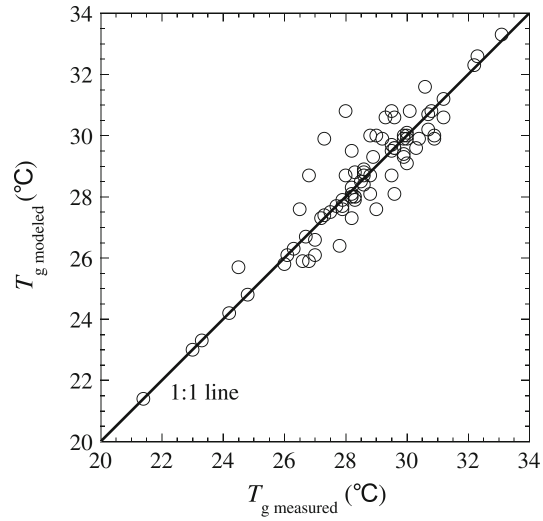


**Fig. 8** Comparison between measured and modeled $T_g$

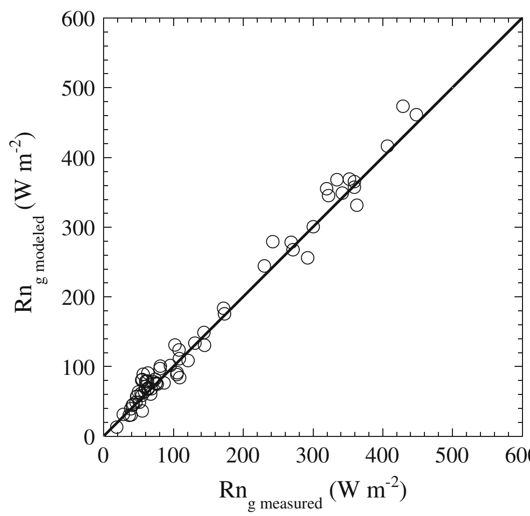


**Fig. 9** Comparison between measured and modeled $Rn_g$

based on the field measurement of meteorological data and PAI. In order to solve the energy balance equation beneath the rice canopy, the radiation balance equation was applied. Shortwave and downward longwave radiation beneath the canopy ($SR_g$ and $L_{dg}$) was parameterized by an inclination factor of the plant body ($F$), PAI and temperature of the bottom side of canopy ($T_c$). Sensible and latent heat flux beneath the rice canopy ($LE_g$ and $H_g$) were expressed by bulk equations with water surface temperature ($T_g$) and bulk transfer coefficient beneath the canopy ($C_{Hg}$). $C_{Hg}$ was parameterized by PAI with a logarithmic equation. Soil heat flux ($G$) was modeled by the force restore model. By compiling all of these sub-models ($SR_g$, $L_{dg}$, $C_{Hg}$, and $G$) into radiation and energy balance equations, the $T_g$ and $Rn_g$ were calculated. $LE_g$ was predicted by bulk equation with parameterized $C_{Hg}$ and calculated $T_g$. There were no

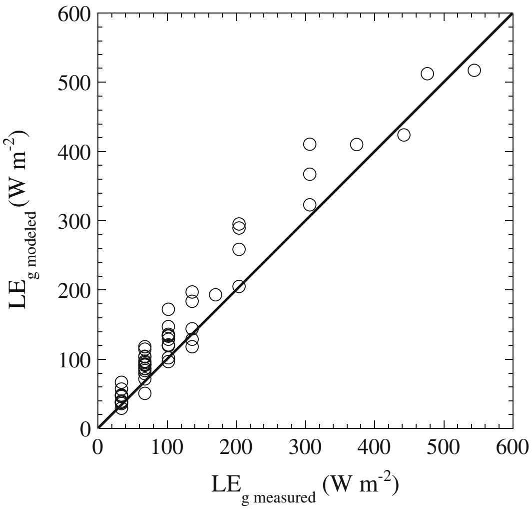


**Fig. 10** Comparison between measured and modeled $LE_g$

significant differences found by comparing measured and modeled $T_g$, $Rn_g$, and $LE_g$. It can be concluded that these submodels of $SR_g$, $L_{dg}$, $C_{Hg}$, and $G$ can be applied to predict the water surface evaporation beneath the rice canopy.

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