Determination of crop and soil evaporation coefficients for estimating evapotranspiration in a paddy field

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Abstract: Accurate estimation of evapotranspiration is important in efficient water management for improving water use efficiency. In order to obtain evapotranspiration and evaporation beneath the canopy using the Food and Agriculture Organization (FAO) method, pan evaporation was used instead of reference evapotranspiration calculated by the Penman-Monteith equation with detailed meteorological data. The total crop coefficient and soil evaporation coefficient were determined using actual measured daytime evapotranspiration and evaporation by the Bowen ratio energy balance and lysimeter, respectively, in a rice paddy field in Japan. The average evapotranspiration was 5.3 mm/d, 4.4 mm/d, 7.4 mm/d and 6.3 mm/d and crop coefficient was 0.79, 1.18, 1.01 and 0.86 for the initial stage, development stage, middle-season stage and late-season stage, respectively. The evaporation was low and almost constant with an average value around 0.77 mm/d when the leaf area index (LAI) reached 3. The proposed average crop coefficients for different growing stages were applied to estimate daytime evapotranspiration and found suitable. A simple soil water evaporation coefficient model was developed using leaf area index for practical use and it was found that it could accurately estimate evaporation.

Keywords: evapotranspiration, evaporation, paddy field, lysimeter, leaf area index (LAI), Bowen ratio energy balance

DOI: 10.25165/j.ijabe.20171004.2290

1 Introduction

Rice is an important staple food crop in Japan,

occupying an area of 2.62 million hm^2 corresponding to over 50% of total agricultural land[1,2]. Proper irrigation scheduling and water supply is very important to improve rice yield and quality[3,4]. Crop evapotranspiration (ET_c) is the main component of water consumption in rice fields; accurate estimation of ET_c is important in efficient water management and improving water use efficiency[5-11]. To estimate ET_c, crop coefficient (K_c), which is the ratio of ET_c to reference evapotransipration (ET_0), is often used because of its simplicity, practicability and its acceptable accuracy. Up to now, numerous studies on evapotranspiration and crop coefficient in rice fields have been presented in different areas of the world. Mohan and Arumugam[12] developed a K_c model for rice grown under lowland conditions in a sub-humid tropical climate in India using meteorological

and lysimeter data.   They found that estimated K_c were higher than the values recommended by the FAO. Tyagi et al.[13] presented mean K_c values of 1.15, 1.23, 1.14 and 1.02 for initial, development, mid-season and late season stages, respectively, for the semiarid conditions of India.   Hwan et al.[14] presented K_c values between 0.78 and 1.58 for transplanted paddy rice in the nine regions of Korea.   Attarod et al.[15] reported an average K_c equal to 0.95 for paddy rice in the tropical climate of Thailand.   Spanu et al.[16] obtained different K_c using the Penman-Monteith equation and pan evaporation in sprinkler irrigation rice in Sardinia, Italy. Different K_c values of 0.95, 1.00 and 0.97 were also reported for aerobic rice for the initial, mid-season and ripening stages, respectively, in the Philippines[17]. Moratiel and Martinez-Cob[18] determined ET_c and K_c for sprinkler irrigated rice for the semiarid conditions of Northeast Spain using the surface renewal method.   As seen from the literature, 1) different K_c values of rice were obtained as a function of the climatic conditions and the management practices of the study area[13,17], or due to the different methods (Penman-Monteith equation and pan evaporation) for ET_0 estimation; 2) the studies on ET_c and K_c in rice paddy fields using the FAO K_c method were scarcely found in Japan[19]; and 3) most studies estimated K_c based on detailed meteorological data using the Penman-Monteith equation.   However, the meteorological data required for use in the Penman-Monteith equation are not always available in some areas.   Keeping these points in mind, the aims of the present study were to 1) determine the crop coefficient for paddy rice in Japan using actual measured ET_c using the Bowen ratio energy balance method and pan evaporation; 2) compare the derived crop coefficient from pan evaporation ($K_{c\ pan}$) with previous studies; and 3) validate the ET_c estimation procedure using average $K_{c\ pan}$ and pan evaporation. Moreover, in order to estimate the contribution of evaporation from the soil surface of the paddy field, the soil water evaporation coefficient was determined using actual measured evaporation by lysimeter and pan evaporation.   The simple soil water evaporation coefficient model was constructed using leaf area index.

2   Materials and methods

2.1   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) in 2009 and 2010. *Oryza sativa* L. cv. Akita-Komachi, which is one of the main cultivars of rice in Japan, was used for the experiment.   The rice plants were transplanted into the field on May 30 with 25 cm spacing between the rows, and 20 cm spacing within a row (a planting density of 20 hills per square meter), and harvested on September 3, 2009.   In 2010, the rice plants were transplanted into the field on May 28 and harvested on August 27 with the same planting density.   The elements of radiation balance, *i.e.* (1–*alb*)*SR* and *Ld–Lu*, were measured with a CNR-2 (Kipp & Zonen, the Netherlands) at 2.5 m and thus the net radiation (*Rn*) was calculated.   Here, *SR* is the global solar radiation, *alb* is the albedo of the paddy field, *Ld* is the downward long wave radiation from the atmosphere and *Lu* is the upward long wave radiation from the paddy field.   In addition, the global solar radiation was measured at 2 m height with a second sensor (Decagon, USA, model LI-200SL).   *Ld* was also measured with a PRI-01 (Prede, Japan) at 2 m height and *Lu* was estimated using these measurements.   Soil heat flux was measured at 2 cm depth with a soil heat plate HFT3 (Campbell, USA), and water surface temperature (T_g) was measured with a thermocouple sensor.   Vertical profiles (0.5 m, 1.0 m and 2.0 m) of air temperature (*T*) and relative humidity above the canopy were measured with psychrometers HMP-45A (Vaisala, Finland) equipped with handmade ventilation fans and mounted in PVC pipes.   The lowest sensor was moved up to about 10 cm above plant height with the growth of rice.   The accuracy of the psychrometers had been validated before the field observation.   Wind speed was measured with three three-cup anemometers 014A (MetOne, USA) at the same height as *T*.   All the data were sampled every 10 s, averaged every 10 min and recorded by a data logger CR23X (Campbell, USA).   Leaf area was measured by sampling 3 rice plants every 7 d or 10 d.   The upper side area of each leaf was measured and average leaf area for

1 plant was calculated. The leaf area index (LAI) was calculated with plant density and leaf area for 1 plant. Plant height was measured with 10 fixed rice plants at same time with leaf area measurement.

The evapotranspiration (ET_c) was estimated using Bowen ratio energy balance method. Water surface evaporation beneath the rice canopy (E_g) was measured by a lysimeter. The lysimeter, size of which was 20 cm × 60 cm × 30 cm (width × length × depth), 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 observing the decrease in water level in the lysimeter, which was measured at 8:00 and 18:00 every day from July 6 to September 3, 2009

and from June 2 to August 27, 2010. In the same manner, the pan evaporation above the rice plant was measured using a round brown pan (20 cm in diameter × 25 cm in depth) which was set on a piece of wood plate surface at a height of 1.5 m. The water depth within the pan was always kept higher than 2 cm. The water depth in the paddy field was measured every day at the same time as lysimeter measurement. In this study, we focused on modeling daytime ET_c and E_g, because nighttime ET_c and E_g were relatively small compared with daytime ET_c and E_g.

The meteorological conditions during the rice growth periods in 2009 and 2010 are shown in Figure 1.
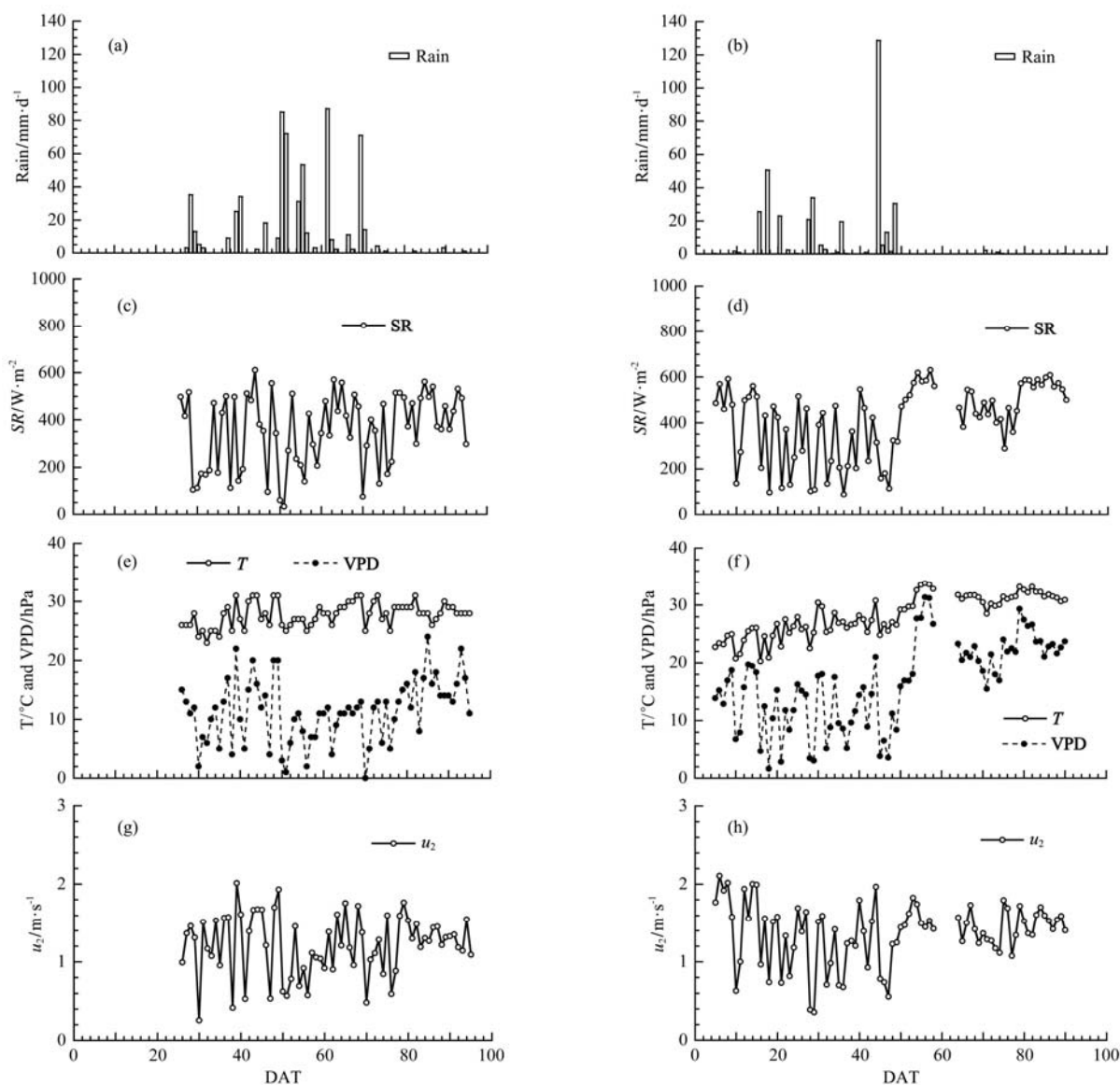

Figure 1   Seasonal variation in meteorological conditions: (a) and (b) rainfall in 2009 and 2010, (c) and (d) solar radiation (SR), (e) and (f) air temperature (*T*) and vapor pressure deficit (VPD), (g) and (h) wind speed at 2 m height (*u₂*), from 26 d to 95 d after transplanting (DAT) in 2009 (June 26-September 3) and 5 DAT to 90 DAT in 2010 (June 2-August 26)

The recorded rainfall during the crop growth season was 630 mm and 369 mm for 2009 and 2010, respectively. The observation of meteorological data in 2009 started from 26 d after transplanting (DAT). The average solar radiation and temperature was similar for both years, although the values from 50 DAT in 2010 were higher than in 2009 due to less rainfall in 2010. The mean vapor pressure deficit (VPD) was higher in 2010 than that in 2009, particularly during the middle and late season of crop growth. The average wind speed was relatively similar between years, with average values of 1.2 m/s and 1.3 m/s for 2009 and 2010, respectively.

2.2   Methodology

2.2.1   Actual evapotranspiration

In this study, the actual evapotranspiration (ET_c) was calculated using the Bowen ratio energy balance method by summing the hourly values. Daytime latent heat flux was obtained based on the heat balance at the canopy surface expressed by the rearranged energy balance equation as follows:

$$LET = \frac{Rn - G - \Delta W}{1 + \beta} \tag{1}$$

where, LET is the latent heat flux density, W/m^2; Rn is the net radiation, W/m^2; G is the soil heat flux density, W/m^2; ΔW is the heat storage in the water layer, W/m^2; β is the Bowen ratio.

The heat storage ΔW is expressed as:

$$\Delta W = c_w \rho_w d_w \frac{dT_w}{dt} \tag{2}$$

where, c_w is the specific heat of water (c_w = 4.18 J/kg·K), d_w is the depth of the water layer beneath the rice canopy, m; ρ_w is the density of water, kg/m^3; T_w is the water temperature at time t, °C.

2.2.2   Reference evapotranspiration

Most researchers calculate reference evapotranspiration ET_0 using the FAO Penman-Monteith method from daily meteorological variables (air temperature, relative humidity, net radiation and wind speed) as:

$$ET_0 = \frac{0.408\Delta(R_n - G) + \gamma \dfrac{C_1}{T_a + 273} u_2(e_s - e_a)}{\Delta + \gamma(1 + C_2 u_2)} \tag{3}$$

where, R_n is net radiation, MJ/(m^2·d); G is soil heat flux density, MJ/(m^2·d); T_a is mean daily air temperature at

2 m height, °C; u_2 is wind speed at 2 m height, m/s; e_s and e_a are saturation and actual vapour pressure (kPa) respectively; Δ is the slope of the saturation vapour pressure curve at air temperature T_a, kPa/°C; γ is the psychrometric constant, kPa/°C; C_1 and C_2 are constants and depend on the reference crop type and calculation time step.

From above equations, we found detailed meteorological data are needed using Equation (3) to estimate the ET_0. In this study, we made a new definition for crop coefficients as described below.

2.2.3   Crop coefficients

According to the FAO-56 method, the crop coefficient K_c could be expressed as:

$$K_c = ET_c / ET_0 \tag{4}$$

when the dual crop coefficient approach[20] is adapted, the Equation (4) could be expressed as:

$$K_c = K_{cb} + K_e = (E_t + E_g) / ET_0 \tag{5}$$

where, K_{cb} is the basal crop coefficient; K_e is the soil water evaporation coefficient beneath the canopy; ET_c is actual evapotranspiration, mm/d; E_t is plant transpiration, mm/d; E_g is the evaporation from soil surface beneath the canopy, mm/d; ET_0 is reference evapotranspiration, mm/d.

The Penman-Monteith Equation is often used to calculate ET_0 precisely. However, in order to calculate ET_c and E_g when meteorological data are not available, we applied pan evaporation (E_{pan}) to determine the K_c and K_e instead of ET_0 calculated from the Penman-Monteith Equation. The evaporation rate from pans filled with water is easily obtained, and pans provide a measurement of the integrated effect of radiation, wind speed, temperature and humidity on evaporation from an open water surface. Although several factors such as reflection of solar radiation and storage of heat within the pan produce differences in loss of water from a water surface (E_{pan}) and from a cropped surface (ET_0)[20], Yan et al.[10] applied E_{pan} to determine E_g in a bare field in the same research area and found it suitable. So, the crop coefficient which was calculated by pan evaporation ($K_{c\,pan}$) could be expressed as:

$$K_{c\,pan} = K_{cb\,pan} + K_{e\,pan} = (E_t + E_g) / E_{pan} \tag{6}$$

where, $K_{cb\,pan}$ is the basal crop coefficient calculated by

pan evaporation; $K_{e\ pan}$ is the soil water evaporation coefficient calculated by pan evaporation; E_{pan} is water surface evaporation above the rice canopy measured using a round pan.

In this study, standard conditions were considered, namely, there was no soil water and salinity stress in the present paddy field since the soil was flooded for most of

the growth period.

Following the FAO-56 approach[20], the growth season of the rice crop is divided into four stages: the initial stage, the crop development stage, the mid-season stage and the late season stage. The divided growth stages for the rice crop and the main features of each stage are given in Table 1.

Table 1   Developmental stages for paddy rice observed in 2009 and 2010

Year	Transplanting date	Harvest date	Initial stage/d	Development stage/d	Mid-season stage/d	Late-season stage/d	Total/d
			Tillering	Panical initiation	Flowering and grain formation	Grain growth and maturity	
2009	30 May	3 Sep	15	30	30	20	95
2010	28 May	27 Aug	15	30	30	15	90

In the paddy field, we think that soil evaporation occurs at the maximum rate limited only by energy availability at the soil surface.   In this case, the soil coverage would be a main influencing factor on soil evaporation.   A simple $K_{e\ pan}$ sub-model was constructed by analyzing the relationship between LAI and the soil evaporation coefficient $K_{e\ pan}$.

For validation of the soil water evaporation coefficient model, the statistical error between modeled and measured soil evaporation was calculated and two-tail t-test statistical analysis method was used with the data from 2009.

3   Results and discussion

3.1   Variation of plant height and LAI

The crop height and LAI of rice in 2009 and 2010 are shown in Figure 2.   The rice plant reached a maximum height of 1.1 m and 1.0 m for 2009 and 2010, respectively, approximately 65-75 DAT.   The maximum plant height was higher than the values (0.7 m) reported by Moratiel and Martinez-Cob[18] for the same cultivar of rice.   The measured LAI exceeded 1.0 around 30 DAT and reached a maximum value of 7.02 in 2009 and 5.13 in 2010.
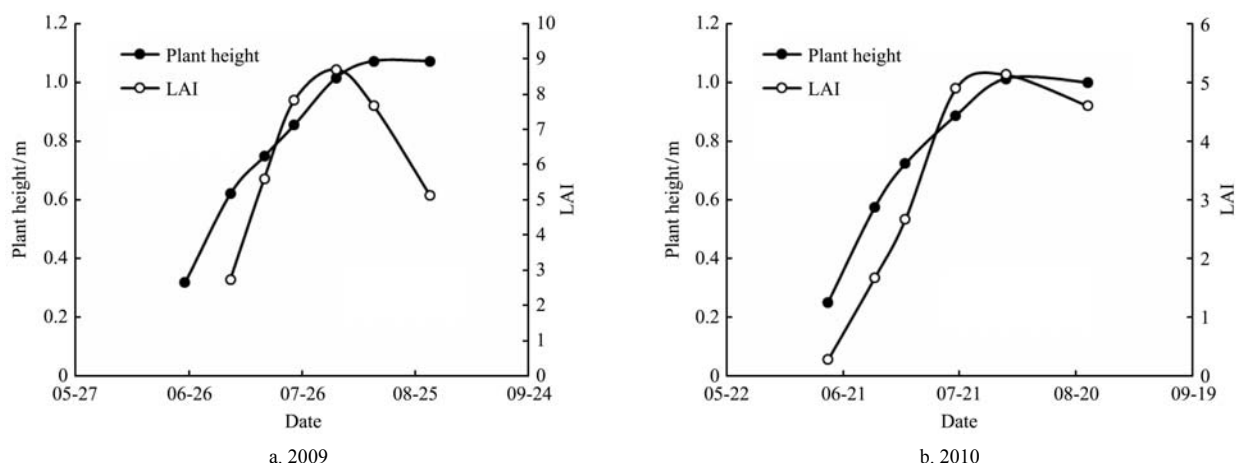

a. 2009

b. 2010

Figure 2   Evolution of plant height and leaf area index (LAI) during rice growing seasons in 2009 and 2010; the transplanting and harvesting dates were May 30 and September 3 in 2009 and May 28 and August 27 in 2010

3.2   Variation of actual evapotranspiration and evaporation

In this study, the actual evapotranspiration (ET_c) was measured using Bowen ratio energy balance method. The ET_c of paddy rice in 2009 and 2010, which was obtained from the Bowen ratio energy balance method, is

shown in Figure 3 together with pan evaporation (E_{pan}) and soil water evaporation beneath the rice canopy (E_g). The field measurement in 2009 started from 26 DAT and from 5 DAT in 2010.   The total ET_c was around 307 mm from 26 DAT to harvest for 2009 and 378 mm from 5 DAT to harvest for 2010.   As described previously, the

whole growth periods were 95 d and 90 d for 2009 and 2010, respectively, and were divided into four stages. The average daytime ET_c was 6.1 mm, 5.7 mm and 5.7 mm for the development stage, middle-season stage and late-season stage, respectively, in 2009 while it was 5.3 mm, 4.4 mm, 7.4 mm, and 6.3 mm for the initial stage, development stage, middle-season stage and late-season stage, respectively, in 2010.   The ET_c for the middle season in 2009 was not higher than the other stages and ET_c for the development stage in 2010 was lower than the other stages.   The difference was mainly due to lower solar radiation during the rainy season (Figure 1). Alberto et al.[17] reported average daytime values of mid-season ET_c of about 5.0 mm, while seasonal ET_c of 500 mm and 434 mm in the Philippines with growing periods of 126 d and 136 d, respectively.   Moratiel and Martinez-Cob[18] reported the average daytime ET_c for mid-season (from 90 DAT to 130 DAT) was about 5.2

mm, while seasonal rice ET_c of 755 mm and 811 mm in Spain with growing periods of 155 d and 165 d, respectively.   The lower seasonal ET_c in this study may be due to the short growing period (95 d and 90 d) and long rainy season during the rice growing periods.   The E_{pan} showed a similar trend with ET_c although E_{pan} was slightly higher than ET_c at the beginning stage and lower than ET_c in the middle stage.   For the late-season, E_{pan} increased to higher than ET_c.   The average E_{pan} during the whole rice growing season was 5.5 mm/d and 5.7 mm/d for 2009 and 2010, respectively.   Water surface evaporation beneath the canopy E_g decreased with the growth of paddy rice because of the increase in the water surface coverage. E_g was low and almost constant with an average value around 0.77 mm/d and 0.75 mm/d for 2009 and 2010, respectively, when the LAI reached 3 (45 DAT)
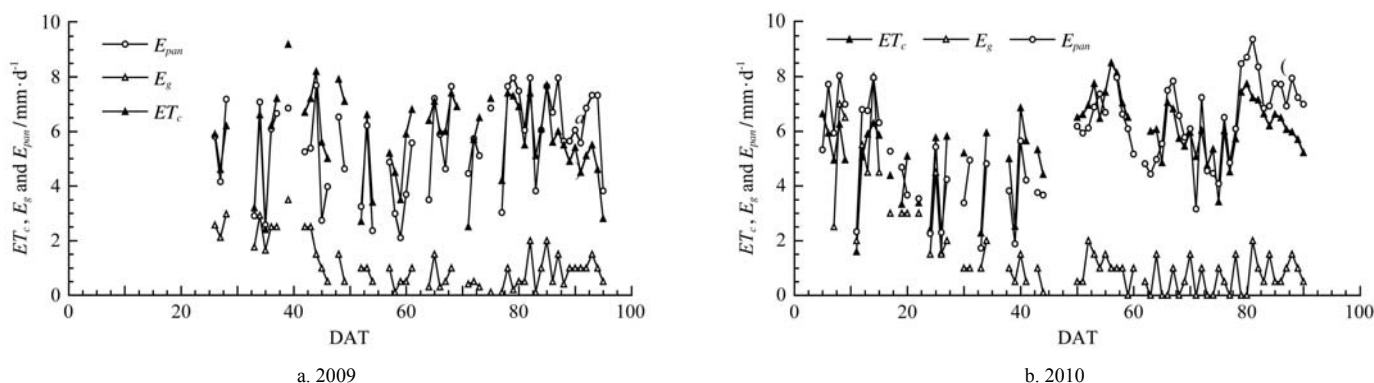

a. 2009   b. 2010

Figure 3   Actual evapotranspiration (ET_c), soil water evaporation beneath the rice canopy (E_g) and pan evaporation (E_{pan}) during rice growing seasons in (a) 2009 and (b) 2010; the transplanting and harvesting dates were May 30 and September 3 in 2009 and May 28 and August 27 in 2010

3.3   Determination of crop coefficient using actual measurements

The total crop coefficient $K_{c\ pan}$ of paddy rice, the basal crop coefficient $K_{cb\ pan}$ and the soil water evaporation coefficient $K_{e\ pan}$ for 2009 and 2010 which were calculated by pan evaporation using Equation (6) are shown in Figure 4.   The coefficient for the initial stage of rice in 2009 is missing because of a lack data. As shown in Figure 4, before around 30 DAT, $K_{e\ pan}$ almost equaled $K_{c\ pan}$ because soil water evaporation beneath the canopy E_g was the main water loss of ET_c. $K_{cb\ pan}$ tended to almost equal $K_{c\ pan}$ because the crop transpiration was the main water loss of ET_c under full

soil surface coverage of the paddy rice after around 30 DAT.   The average $K_{cb\ pan}$ was 0.64, 1.08 and 0.78 for the development stage, middle stage and late season stage in 2009, respectively, and was 0.01, 0.73, 0.76 and 0.73 for the initial stage, development stage, middle stage and late season stage in 2010, respectively.   The average $K_{e\ pan}$ was 0.45, 0.14 and 0.13 for the three stages in 2009 and was 0.78, 0.45, 0.25 and 0.13 for the four stages in 2010.   The average $K_{c\ pan}$ was 1.09, 1.22 and 0.91 for the development stage, middle stage and late season stage in 2009, respectively, and was 0.79, 1.18, 1.01 and 0.86 for the initial stage, development stage, middle stage and late season stage in 2010, respectively.   The range of $K_{c\ pan}$

for 2009 and 2010 was 0.56-1.84 and 0.68-1.76, respectively, which were different from the results reported by the Research Group on Evapotranspiration[21] that $K_{c\,pan}$ values in the range 0.40-1.05 based on the pan evaporation method for rice under Japanese climatic conditions. However, higher values in the range 1.1-1.6 were obtained by Tomar and O'Toole[22] based on pan evaporation in monsoonal Asian countries. Similarly, Rao et al.[23] obtained $K_{c\,pan}$ in the range 0.88-1.99 based on pan evaporation in South India. Reuss[24] presented $K_{c\,pan}$ values in the range 0.80-1.95 under tropical Pakistan climatic conditions. Gupta et al.[25] derived K_c

pan values in the range 0.62-2.32 for rice grown under north Indian climatic conditions. The likely reasons for the difference in $K_{c\,pan}$ between our study and other research are 1) different pan types, size and color used for measuring pan evaporation, 2) different pan heights set above the canopy and the state of upwind buffer zone, 3) different level at which the water is maintained in the pan and 4) irrigation and climate conditions for measuring ET_c. All of those factors may enable an increase or decrease in E_{pan} and ET_c resulting in the different $K_{c\,pan}$ between the present study and other studies.
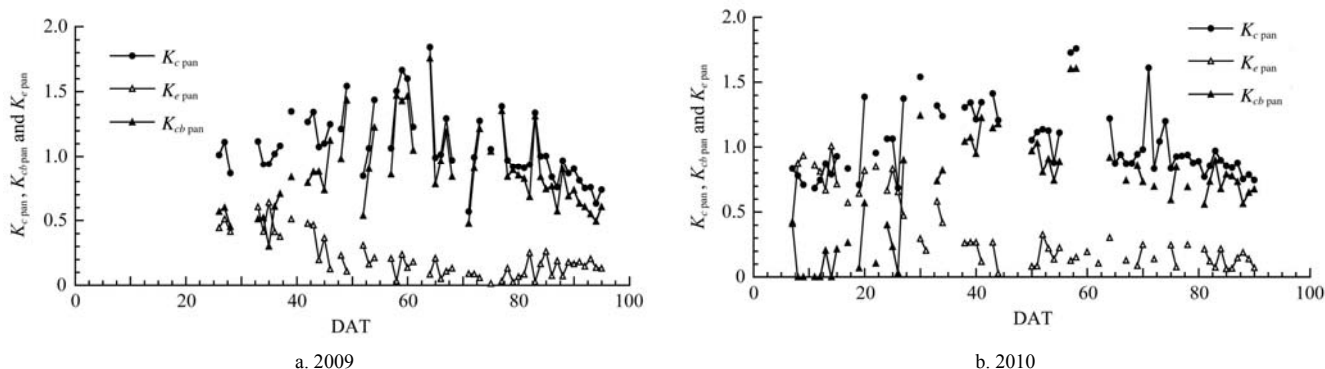

a. 2009   b. 2010

Figure 4   Total crop coefficient ($K_{c\,pan} = ET_c/E_{pan}$), soil water evaporation coefficient ($K_{e\,pan} = E_g/E_{pan}$) and basal crop coefficient ($K_{cb\,pan} = K_{c\,pan} - K_{e\,pan}$) during rice growing seasons in (a) 2009 and (b) 2010; the transplanting and harvesting dates were May 30 and September 3 in 2009 and May 28 and August 27 in 2010

3.4   Validation of average total crop coefficient

It is necessary to validate the accuracy of average $K_{c\,pan}$ for each stage to calculate ET_c for practical use such as irrigation scheduling. We calculated daytime ET_c of paddy field in 2010 using average $K_{c\,pan}$ of 2009. Figure 5 shows the comparison between measured and calculated ET_c for 2010. There was high correlation between measured and calculated ET_c. The regression points were scattered close to 1:1 line with some exceptions. The regressing lines were close to 1:1 which means the calculated ET_c were close to the measured values. The coefficients of determination (R^2) was 0.69. The interception (a) and slope (b) of least-squares regression was 0.72 and 1.86. The other statistical parameters, such as systematic mean square errors (MSE$_s$), unsystematic mean square errors (MSE$_u$) and index of agreement (d) were shown in Table 2. According to two-tail t-test statistical analysis (significant level α=0.05), there were no significant differences

between measured and calculated ET_c. It was revealed that the application of pan evaporation instead of ET_0 from detailed meteorological data for estimation of ET_c was feasible. However, the determined $K_{c\,pan}$ for paddy rice in present study still needs validations based on more data in other different climate areas.
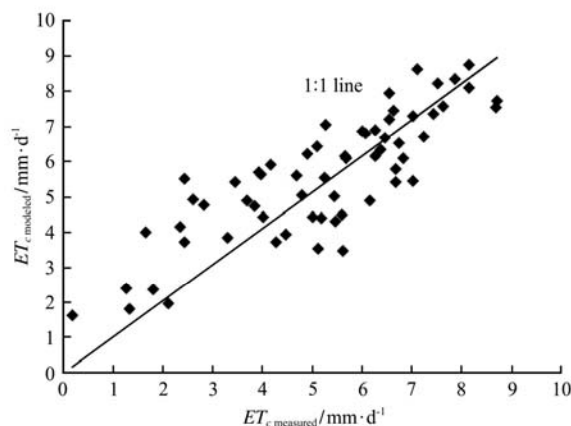

Figure 5   Comparison of calculated ET_c using average crop coefficient $K_{c\,pan}$ with measured values in 2010; the transplanting and harvesting dates were May 28 and August 27 in 2010

Table 2   Error analysis statistics of the comparison between measured and predicted ET_c during 2009 and 2011

Year	P	M	a	b	R^2	RMS	MSE_s	MSE_u	d
2010	5.55	5.58	0.72	1.86	0.69	1.72	0.21	0.93	0.89

Note: P and M are mean predicted and measured ET_c, respectively; a and b interception and slope of least square regression line, R^2 coefficients of determination, RMS root mean square error, MSE_s systematic mean square error, MSE_u unsystematic mean square error, d index of agreement; b, R^2 and d are dimensionless, while the remaining terms have the unit of mm/d.

3.5   Simple model for soil water evaporation coefficient beneath the rice canopy

The FAO recommends determining soil evaporation coefficient using the energy and water available for evaporation at the soil surface[20].   In the paddy rice field, the soil surface was flooded by water for almost the whole growth period except for some days in the late season; so, we assumed that the percentage of energy that reached the soil surface is the only factor affecting soil water evaporation beneath the rice canopy.   We applied LAI to simulate soil evaporation coefficient $K_{e\,pan}$.   As shown in Figure 6, there was a negative relationship between K_e and LAI.   The relationships between LAI and K_e were constructed using the data from 2009 (Equation (7)) and 2010 (Equation (8)):

$$K_{e\,pan} = 0.43 - 0.16\log(LAI) \quad R^2 = 0.72 \qquad (7)$$

$$K_{e\,pan} = 0.46 - 0.16\log(LAI) \quad R^2 = 0.51 \qquad (8)$$
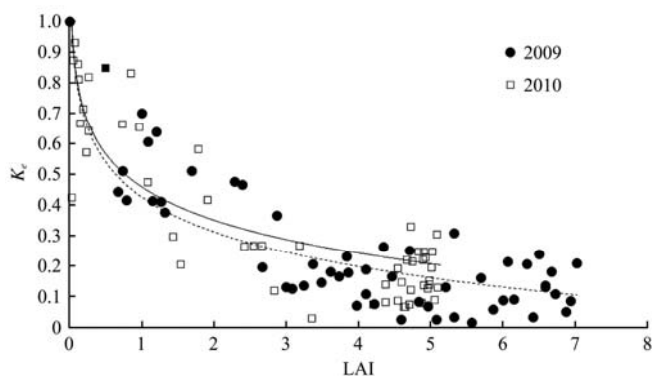

Figure 6   Correlation between leaf area index (LAI) and soil water evaporation coefficient ($K_{e\,pan}$) for 2009 and 2010

The above equations obtained based on the data from 2009 and 2010 showed quite similar coefficients.   We used the data from 2009 to validate and assess the model constructed based on the data from 2010, while the data from 2010 to validate and assess the model constructed based on the data from 2009.   The comparisons between measured and modeled soil water evaporation beneath the canopy are shown in Figure 7.   The slopes of regression lines and correlation coefficients are 0.95 and 0.71 for E_g

modeled by E_{pan} based on the data from 2009, while the values are 0.79 and 0.54, respectively, based on the data from 2010.   The advantage of applying E_{pan} to estimate E_g is that meteorological data are not needed.   This is to facilitate estimating E_g for areas where meteorological data are unavailable. Equations (7) and (8) could be used together with the above recommended total crop coefficient to estimate soil water evaporation beneath the canopy and crop transpiration separately.
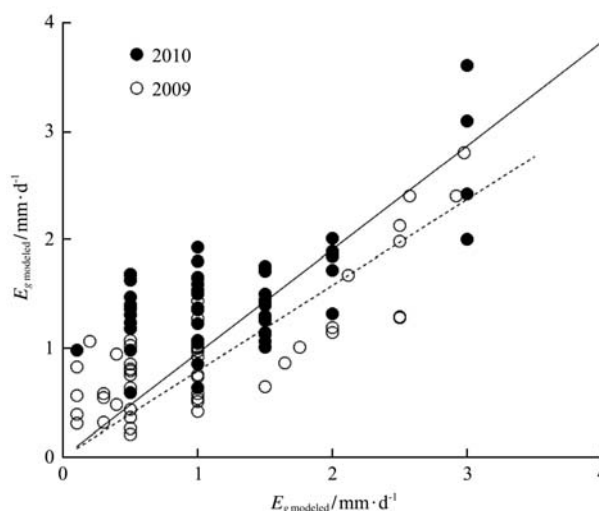

Figure 7   Comparison of measured soil water evaporation beneath the canopy $E_{g\,measured}$ with calculated values $E_{g\,modeled}$ using E_{pan} in 2009 and 2010

4   Conclusions

The FAO recommended crop coefficients methods have often been used to estimate evapotranspiration and evaporation.   In this study, to estimate transpiration and evaporation separately, the total crop coefficient and soil evaporation coefficient were determined based on the actual measurement in a paddy rice field in 2009 and 2010.   In order to obtain evapotranspiration and evaporation beneath the canopy when meteorological data are unavailable, pan evaporation was applied to determine the total crop coefficient and the soil water evaporation coefficient instead of reference evapotranspiration calculated by the Penman-Monteith Equation.   The

average total crop coefficient was taken for the four rice growth stages.   To verify the accuracy of determined average $K_{c\,pan}$ for each stage, evapotranspiration was reproduced using average $K_{c\,pan}$ based on different data set.   It was found that there were no significant differences between measured and reproduced evapotranspiration.   The soil evaporation coefficient was modeled using LAI with data from 2009 and 2010 using logarithmic equations.   The performance of the $K_{e\,pan}$ models were verified by comparing the calculated and measured evaporation.   As a result, evaporation could be estimated using the constructed $K_{e\,pan}$ model.   By combining the $K_{e\,pan}$ model and the $K_{c\,pan}$ values for each stage, soil water evaporation beneath the rice canopy and transpiration could be estimated separately without using any meteorological data.

Acknowledgements

[References]

[1]   Sato H.   The current state of paddy agriculture in Japan.   Irrig Drain, 2001; 50: 91–99.

[2]   Yu F H, Xu T Y, Cao Y L, Yang G J, Du W, Wang S.   Models for estimating the leaf NDVI of japonica rice on a canopy scale by combining canopy NDVI and multisource environmental data in Northeast China.   Int J Agric & Biol Eng, 2016; 9(5): 132–142.

[3]   Liu X, Bian C, Ma C, Liu Q, Wei C, Li Q.   Yield loss compensation effect and water use efficiency of widely and precisely sowed winter wheat covered under corn stalks.   Journal of Drainage and Irrigation Machinery Engineering,

2015; 33(9): 811−817. (in Chinese)

[4]   Fu Q, Meng F X, Li T X, Liu D, Gong F L, Osman A, et al.   Cloud model-based analysis of regional sustainable water resource utilization schemes.   Int J Agric & Biol Eng, 2016; 9(5): 67–75.

[5]   Allen R G, Pereira L S, Smith M, Raes D, Wright J L.   The FAO-56 dual crop coefficient method for predicting evaporation from soil and application extensions.   J. Irrig Drain Eng., 2005; 131(1): 2–13.

[6]   He B, Oue H, Wang Y, Takase K.   Micrometeorological model for estimating evapotranspiration from a wheat Field in the Hetao Irrigation District of Yellow River Basin.   Proceeding of JSIDRE, 2005; 60: 179–182.

[7]   He B, Oue H, Wang Y, Takase K.   Measurement and modeling of evapotranspiration from an irrigated wheat field in the Hetao irrigation district of the yellow river basin, J Japan Soc Hydro Water Resource, 2007; 20: 8–16.

[8]   Yan H, Oue H.   Application of the two-layer model for predicting transpiration from the rice canopy and water surface evaporation beneath the canopy.   J Agric Meteorol, 2011; 67(3): 89–97.

[9]   Yan H, Oue H, Zhang C.   Predicting water surface evaporation in the paddy field by solving energy balance equation beneath the rice canopy.   Paddy and Water Environment, 2012; 10(2): 121–127.

[10]   Yan H, Zhang C, Oue H, Sugimoto H.   Comparison of different methods for estimating soil surface evaporation in a bare field.   Meteorology and Atmospheric Physics, 2012; 118(3-4): 143–149.

[11]   Yan H, Shi H, Oue H, Zhang C, Xue Z, Cai B, et al.   Modeling bulk canopy resistance from climatic variables for predicting hourly evapotranspiration of maize and buckwheat. Meteorology and Atmospheric Physics, 2015; 127(3): 305–312.

[12]   Mohan S, Arumugam N.   Irrigation crop coefficients for lowland rice.   Irrig Drain Syst., 1994; 8(3): 159–176.

[13]   Tyagi N K, Sharma D K, Luthra S K.   Determination of evapotranspiration and crop coefficients of rice and sunflower with lysimeter.   Agric Water Manage, 2000; 45: 41–54.

[14]   Seung Hwan Y, Jin-Yong C, Min Won J.   Estimation of paddy rice crop coefficients for Penman-Monteith and FAO modified Penman method.   ASABE Annual International Meeting, Oregon. 2006.

[15]   Attarod P, Aoki M, Komori D, Ishida T, Fukumura K, Boonyawat S, et al.   Estimation of crop coefficients and evapotranspiration by meteorological parameters in a rain-fed paddy rice field, cassava and teak plantations in Thailand.   J Agric Meteorol, 2006; 62: 93–102.

[16]   Spanu A, Murtas A, Ballone F.   Water use and crop coefficients in sprinkler irrigated rice.   Ital J Agron, 2009;

2: 47–58.

[17] Alberto M C R, Wassmann R, Hirano T, Miyata A, Hatano R, Kumar A, et al.   Comparisons of energy balance and evapotranspiration between flooded and aerobic rice fields in the Philippines. Agric Water Manage, 2011; 98(9): 1417–1430.

[18] Moratiel R, Martínez-Cob A.   Evapotranspiration and crop coefficients of rice (*Oryza sativa* L.) under sprinkler irrigation in a semiarid climate determined by the surface renewal method.   Irrigation Science, 2013; 1–12.

[19] Vu H S, Watanabe H, Takagi K.   Application of FAO-56 for evaluating evapotranspiration in simulation of pollutant runoff from paddy rice field in Japan.   Agric Water Manage, 2005; 76 (3): 195–210.

[20] Allen R G, Pereira L S, Raes D, Smith M.   Crop evapotranspiration: guidelines for computing crop water requirements.   FAO Irrigation and Drainage Paper No. 56. FAO, Rome. 1998.

[21] Research Group on Evapotranspiration.   Evapotranspiration from paddy field.   J Agric Meteorol, Tokyo, 1967; 4(22): 149–158.

[22] Tomar V S, O'Toole J C.   Water use in lowland rice cultivation in Asia: A review of evapotranspiration.   Agric Water Management, 1980; 3: 83–106.

[23] Rao A S, Thomas R, Prabha H.   Evapotranspiration rates of rice varieties Culture-20 and Pattami-20 in a humid tropical climate.   Mausam, 1988; 39(1): 111–112.

[24] Reuss J O.   Matching cropping systems to water supply using an integrative model.   Water Management Technical Repõrt 62, Water Management Research Project, Colorado State University, Fort Collins, Colorado, USA. 1980.

[25] Gupta R K, Chauhan H S, Singh R V.   Estimation and prediction of evapotranspiration of paddy crop using climatic data.   J of Institution of Engineerings (India)-AG, 1987; 67: 90–93.