

Estimating and Validating Soil Evaporation and Crop Transpiration During the HiWATER-MUSOEXE

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Abstract—The two-source energy balance (TSEB) model was successfully applied to estimate evaporation (E), transpiration (T), and evapotranspiration (ET) for land covered with vegetation, which has significantly important applications for the terrestrial water cycle and water resource management. However, the current composite temperature separation approaches are limited in their effectiveness in arid regions. Moreover, E and T are difficult to measure on the ground. In this letter, the ground-measured soil and canopy component temperatures were used to estimate E, T, and ET, which were better validated with observed ratios of E (E/ET%) and T (T/ET%) using the stable oxygen and hydrogen isotopes, and the ET measurements using an eddy covariance (EC) system. Our results indicated that even under the strongly advective conditions, the TSEB model produced reliable estimates of the E/ET% and T/ET% ratios and of ET. The mean bias and root-mean-square error (RMSE) of E/ET% were 1% and 2%, respectively, and the mean bias and RMSE of T/ET% were -1% and 2%, respectively. In addition, the model exhibited relatively reliable estimates in the latent heat flux, with mean bias and RMSE values of 31 and 61 $W \cdot m^{-2}$, respectively, compared with the measurements from the EC system. These results demonstrated that a robust soil and vegetation component temperature calculation was crucial for estimating E, T, and ET. Moreover, the separate validation of E/ET% and T/ET% provides a good prospect for TSEB model improvements.

Index Terms—Evapotranspiration (ET) estimation, soil and vegetation component temperatures, validation.

I. INTRODUCTION

ONE-source evapotranspiration estimation models combine the soil-vegetation components into a single source. However, in real landscape conditions, the surface is heterogeneous and contains a mixture of soil and vegetation having different temperatures and resistance to energy exchange. Therefore, one-source models explicitly cannot estimate the surface evapotranspiration accurately because the effect of background soil versus canopy temperatures is not properly treated. To overcome the limitation of one-source models,

Shuttleworth and Wallace proposed a typical two-source evapotranspiration estimation model in which the energy partition is assumed to occur in both “the above canopy” and “the under soil” cases. Water vapor and heat meet over the reference height in the interior of the canopy. Moreover, the mixed water vapor and heat can only exit through the top of the canopy; the total heat flux is in addition to the fluxes coming from every surface layer [1]. However, the model is complex, having over five resistances that cannot be accurately calculated. In addition, the model includes required parameters and observations that cannot be readily obtained from operational satellite- and ground-based data; therefore, the range of applications of the model is limited [2]. To simplify the complex two-source evapotranspiration estimation model, Norman *et al.* proposed the parallel and simplified series two-source energy balance (TSEB) model to estimate the soil evaporation (E) and plant transpiration (T) separately. The model has undergone several revisions, improving the estimation of soil and canopy net radiation, the aerodynamic resistance of the soil surface, the fractional vegetation coverage observed at the radiometer view angle, the distribution of regional-scale near-surface air temperature, and soil and canopy component temperatures [3]–[6]. In addition, the series model is often used instead of the parallel model, allowing for interaction between the soil and the canopy.

Because the TSEB model only requires the surface energy balance model with a single measurement of land surface temperature, the original model and subsequent refinements have been widely used to estimate E and T under a wide variety of vegetation types, vegetation coverage, climates, and spatial scales [7]. However, most studies have only evaluated the total fluxes or ET (soil plus canopy) in comparison with measurements using the Bowen ratio–energy balance) system, the eddy covariance (EC) system, or the large aperture scintillometer. Despite this limitation, the separation of E and T measurements is possible using, for example, microlysimeters and sap flow gauges, respectively, as demonstrated by Colaizzi *et al.* However, these measurements can only be implemented at the canopy scale rather than at the field scale and are also generally very labor intensive and difficult to perform [7]. Therefore, we propose an alternative method in which the E/ET and T/ET ratios are estimated using the stable oxygen and hydrogen isotope technique. In addition, the soil and vegetation component temperatures are separated from the composite surface temperature using the Priestly–Taylor or Penman–Monteith models, which assume non-water-stressed conditions. However, this assumption may be invalid in the limited irrigation areas and dryland; thus, other alternative methods are desired.

Manuscript received January 24, 2014; revised May 21, 2014 and June 21, 2014; accepted July 8, 2014. This work was supported in part by the National Natural Science Foundation of China under Grant 91125002 and in part by the Fundamental Research Funds for the Central Universities. (*Corresponding author: Shaomin Liu.*)

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Digital Object Identifier 10.1109/LGRS.2014.2339360

The objective of this letter is to estimate E, T, and ET using the soil and canopy component temperatures observed via a high-resolution thermal camera as inputs to a series TSEB model and to subsequently better validate E, T, and ET using a combination of the stable oxygen and hydrogen isotope technique and EC measurements.

II. MATERIALS AND METHODS

A. Study Site and Data Description

The experimental area is an artificial oasis that is covered with maize, vegetables, and orchards. The site is located in the middle-stream part of the Heihe River Basin, China [9]. In this letter, the field observations were obtained from the Daman superstation installed in the central oasis, which is a 40-m boundary layer tower located at 100.3722° E, 38.8555° N and at an elevation of 1556 m. Data of day of year (DOY) 170, 173, 176, 192, 195, 231, 252, and 256 were used to determine ET and the ratios of E (E/ET%) and T (T/ET%) to ET during the Multi-Scale Observation Experiment on Evapotranspiration over heterogeneous land surfaces, which was part of the Heihe Water Allied Telemetry Experimental Research (HiWATER-MUSOEXE) [9], [10]. The meteorological parameters were measured every 10 min and included air temperature, wind speed, humidity at 5 m over the ground, four-component radiations (measured at 12 m above the ground using a four-component radiometer), and turbulent fluxes (measured at 4.5 m above the ground using an EC system with a sampling frequency of 10 Hz). The recorded raw data were processed using Edire software (<http://www.geos.ed.ac.uk/abs/-research/micromet/EdiRE/>) and finally averaged over 30 min [10]–[12]. The soil heat fluxes were measured using three heat plates located 6 cm under the ground. Two plates were buried under the bare soil between two maize plants, and another plate was buried under the maize plant. The surface soil heat flux (G) can be calculated using the vegetation fraction weighted average of the three heat-plate measurements, combined with the PlateCal approach proposed by Liebenthal *et al.* [13]. A Fluke Ti55 thermal infrared camera was manually operated on a 25-m-high platform on a boundary layer tower to measure the thermal radiation of the cropland approximately every 120 min; the observations were collected as thermal images from approximately 07:00 to 19:00 China Standard Time (CST) during the daytime. Next, the soil and canopy component temperatures were simulated using the thermal images and validated by surface temperature calculated from the four-component radiations. There were continuous measurements of the D/H (the ratio of the two atoms in the deuterated water) and the $\delta^{18}\text{O}$ isotope ratios of the water vapor in the atmosphere at the Daman superstation. The ground-based measurement data were applied to partition ET into E and T applying the Craig–Gordon model [14]. Finally, the auxiliary data of the soil and vegetation emissivities were manually measured using a hand portable remote sensing FT-IR spectrometer (102 F) [15]. The leaf area index (LAI) was measured using an LAI-2000 apparatus, and the plant width, plant height, leaf width, and leaf length were measured at samples sites on the ground [16].

B. Methodology

The TSEB model was originally proposed by Norman *et al.* [2] and improved by Colaizzi *et al.* [7]. This model can be formulated with most soil–plant–atmosphere energy balance algorithms and divided into canopy and soil layers, i.e.,

$$\text{Rn}_s = H_s + \text{LE}_s + G_0 \quad (1)$$

$$\text{Rn}_c = H_c + \text{LE}_c \quad (2)$$

where Rn is net radiation, G_0 is surface soil heat flux, and H and LE are the sensible and latent heat fluxes, respectively; the subscripts c and s refer to canopy and soil, respectively. Moreover, Rn_c and Rn_s were estimated using the method proposed by Morillas *et al.* [8]; the modifications are described in Colaizzi *et al.* [4], [7]. The formulations are as follows:

$$\begin{aligned} \text{Rn}_s &= \tau_{\text{longwave}} L_{\downarrow} + (1 - \tau_{\text{longwave}}) \varepsilon_c \sigma T_c^4 - \varepsilon_s \sigma T_s^4 \\ &\quad + \tau_{\text{solar}} (1 - \alpha_s) S_{\downarrow} \end{aligned} \quad (3)$$

$$\begin{aligned} \text{Rn}_c &= (1 - \tau_{\text{longwave}}) (L_{\downarrow} + \varepsilon_s \sigma T_s^4 - 2\varepsilon_c \sigma T_c^4) \\ &\quad + (1 - \tau_{\text{solar}}) (1 - \alpha_c) S_{\downarrow} \end{aligned} \quad (4)$$

where σ is the Spann–Boltzmann constant. S_{\downarrow} and L_{\downarrow} are the incoming short- and long-wave radiation from the sky, respectively, in $\text{W} \cdot \text{m}^{-2}$; the two terms were observed by the four-component radiometer above the ground. Moreover, T_s and T_c are the soil and vegetation component temperatures, respectively, in K, which were simulated using the measured thermal images from the thermal camera; α_s and α_c are the soil and vegetation albedo, respectively. α_s is calculated using the fractions of short-wave radiation in the photosynthetically active radiation and NIR bands, where assuming soil reflectance to 0.15 and 0.25, respectively, over dry bare soil [4]. Furthermore, τ_{longwave} and τ_{solar} are the long- and short-wave radiation transmittances through the canopy, respectively. Here, τ_{longwave} can be calculated using the ground-based LAI measurements, the long-wave radiation extinction coefficient was set to 0.95, and the vegetation clumping factor was calculated according to the work of Anderson *et al.* [17] and Li *et al.* [18].

Next, to evaluate the TSEB model accurately, the soil heat flux was using the ground measurement. In addition, the soil and canopy sensible heat fluxes were estimated using the series TSEB model, and their latent heat fluxes were calculated while solving the energy balance equations (1) and (2), respectively [6].

The soil and canopy component temperatures were calculated using the images obtained with the thermal camera [19]. To calculate the component temperatures, the visible and NIR images were classified into soil and canopy pixels using the maximum-likelihood method. Next, the soil and canopy directional brightness temperatures were exacted from the thermal images [14]. Finally, the thermal infrared temperatures were converted to the radiation temperatures using the incoming long-wave radiation from the sky and the soil and canopy emissivities. Errors in the derived component temperature were primarily caused by image classification errors; these classification errors varied with vegetation abundance. Because of the

TABLE I
STATISTICAL PARAMETERS FOR ESTIMATED VERSUS MEASURED VARIABLES USING THE TSEB MODEL

	Rn (Wm ⁻²)	H (Wm ⁻²)	LE (Wm ⁻²)	E/ET%	T/ET%
N	33	33	33	8	8
Measured average	495	44	394	16	84
Measured SD	155	50	139	5	5
Calculated average	477	49	380	16	84
Calculated SD	172	49	144	5	5
Bias	-18	5	31	1	-1
RMSE	29	19	61	2	2
MAPE %	5%	33%	15%	11%	2%

lack of reliable *in situ* component temperature measurements, to evaluate the accuracy, the calculated component temperatures were converted into composite radiometric temperature with a measured fraction of vegetation and soil and vegetation component emissivities. Next, the simulated radiometric temperatures were validated against the surface radiometric temperatures, which were calculated according to the incoming long-wave radiation observed by the four-component radiometer. The results suggested that the simulated composite temperatures may be overestimated because the mean bias/RMSE for north, south, and east were 0.3/1.6 K, 0.3/1.6 K, and 0.9/1.6 K, respectively; the west had lower accuracy and the mean bias/RMSE of 0.9/1.9 K.

To partition ET into E and T, stable oxygen and hydrogen isotope technology was used at the Daman superstation, which was applied to estimate the $\delta^{18}O$ and δD values of water in xylem or twigs (δx) above the canopy layer [14]. To determine the $\delta^{18}O$ and δD isotopic compositions of ET (δET), E (δE), and T (δT), the value of δE was estimated using the Craig–Gordon model, and δE was approximated under isotopic steady state at midday, incorporating the Péclet effects and non-steady-state effects into a leaf water model. The details of the stable oxygen and hydrogen isotopes technique and the E and T partitioning process were described by Wen *et al.* [14].

III. RESULTS AND DISCUSSION

Accurately estimating surface fluxes in a strongly advective irrigated agricultural area is a particularly challenging task and is even more difficult when the EC flux measurements of *H* and *LE* have an incomplete energy balance closure with respect to the available energy $Rn - G_0$ [21]. The average energy balance ratio, i.e., $(H + LE)/(Rn - G_0)$, which was measured by the EC system from 09:00 to 19:00 CST in the study area, was 93%. Because the acquired energy balance ratio was near unity, the EC closure was not forced. The E/ET% and T/ET% statistics, including the estimates using the TSEB model and the ground-based measurements, are presented in Table I and Fig. 1. During the crop growing season in the study area, the mean value and standard deviation (SD) of the E/ET% measurements were 15.7% and 5.2%, respectively; for the T/ET% measurements,

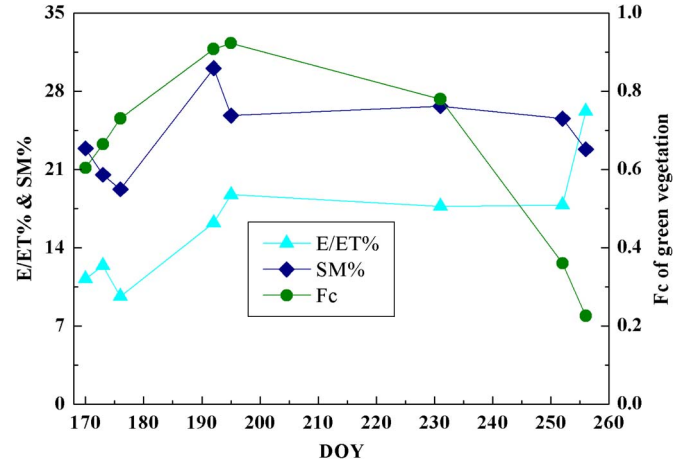


Fig. 1. Assessment of the relationship between the estimated E/ET% using the TSEB model and the two main affecting factors: surface soil moisture (SM) content and fraction of the green vegetation cover.

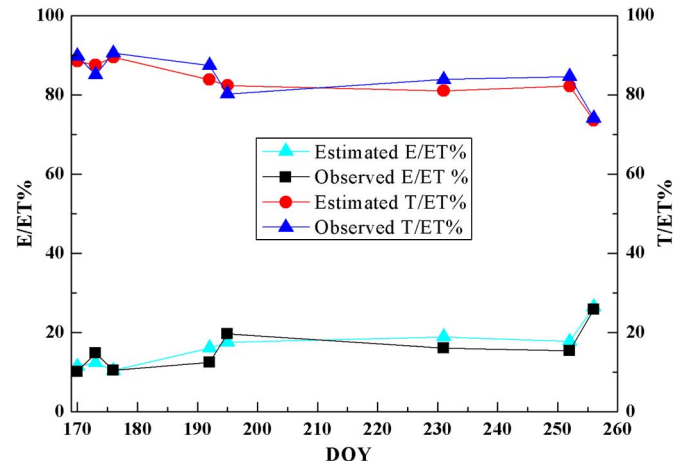


Fig. 2. Comparison of the estimated E/ET% and T/ET% values with the ground-based measurement data using the stable oxygen and hydrogen isotope technique.

the mean value and SD were 84.3% and 5.2%, respectively. However, E/ET% and T/ET% exhibited variability in the early (DOY 170, 173, and 176), middle (DOY 192, 195, and 231), and late growing seasons (DOY 252 and 254), e.g., E/ET% was lower in the early growing season and higher in the late growing season.

To understand the seasonal behavior of evaporation and transpiration clearly, we assessed the relationship between the value of the estimation E/ET% and the two main factors that changed during the entire season: the SM, which was measured at 0.04 m depth in a shallow soil area, and the fraction of green vegetation [20]. The results of analysis (see Fig. 1) indicated that the surface SM factor had a considerable effect over the variable E/ET%. The lower E/ET% occurred during the early season; even the fraction of green vegetation was smaller than that in the middle season, and there was more bare soil area. The unusual phenomenon in this period was attributed to the fact that shallow SM content was lower than the middle and late growing seasons in the study area. The mean value of shadow moisture was 21% in the early season, whereas it was 28% and 24% in the middle and late growing seasons, respectively.

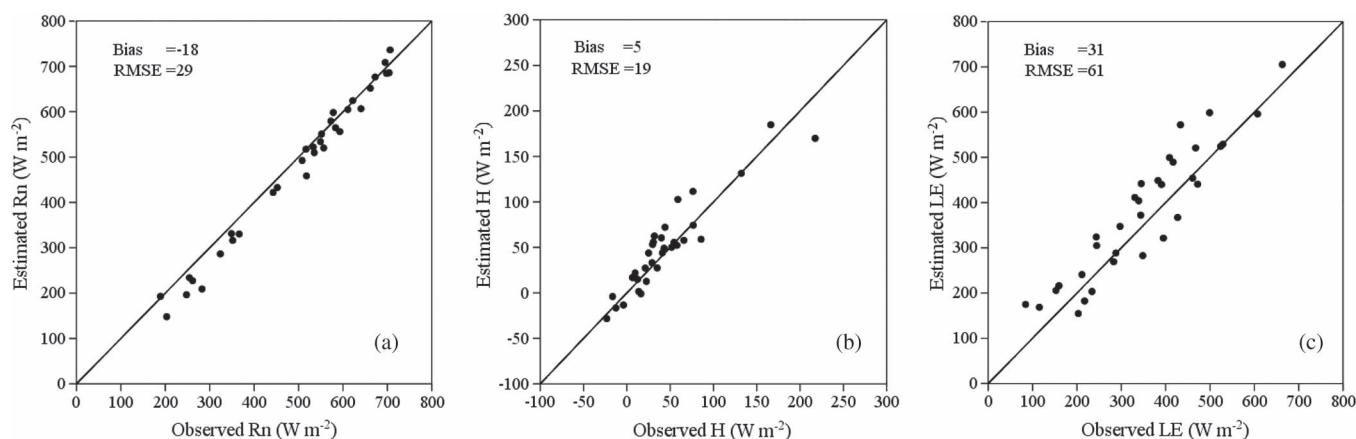


Fig. 3. Scatterplots of the comparison of the energy components derived from the TSEB model with the measurements from a four-component radiometer and an EC system. (a) Rn. (b) H . (c) LE.

Although these surface SM differences were not obvious, it could relate to and affect the soil evaporation [20]. In addition, the higher E/ET% rapidly increased, particularly in the DOY 252 and 256, when most of the maize had withered and the fraction of green vegetation cover was lower than 0.4, while the surface soil was still wet.

The TSEB model-estimated E/ET% and T/ET% values agree well with the values observed using the stable oxygen and hydrogen isotopes technique during the early, middle, and late growing seasons (see Fig. 2). The statistical analysis demonstrated that E/ET% estimated using the TSEB model and applying the soil and canopy component temperatures compared with the ground observations had a mean bias and RMSE of 1% and 2%, respectively. Furthermore, T/ET% was underestimated by -1% . The results demonstrate that the TSEB model can accurately estimate E/ET% and T/ET% by separately estimating E and T. However, a tendency to overestimate E/ET% may result from the underestimation of net radiation when using the residual surface energy balance model to estimate the soil latent heat fluxes.

The statistics for the TSEB model outputs compared with the ground measurements are presented in Table I and Fig. 3. The model exhibited lower errors in net radiation [see Fig. 3(a)]; however, the explained variance and predicted errors were slightly higher for LE and H compared with the measurements. As the measurements indicated that the skies were typically clear on the selected days, solar radiation at the site during the HiWATER-MUSOEXE reached a maximum of over $1000 \text{ W} \cdot \text{m}^{-2}$. The measured surface net radiation at the local solar noon (approximately 13:00) varied from over $700 \text{ W} \cdot \text{m}^{-2}$ during the early and middle growing seasons to $580 \text{ W} \cdot \text{m}^{-2}$ during the late growing season. The high Rn was successfully estimated using the TSEB model; the bias, RMSE, and mean absolute percentage error (MAPE) were $-18 \text{ W} \cdot \text{m}^{-2}$, $29 \text{ W} \cdot \text{m}^{-2}$, and 5%, respectively. However, a tendency for the model to underestimate Rn was observed. We can deduce that this underestimation of Rn may be caused by the overestimation of the canopy temperatures according to (3) and (4), although the validations are absent. Due to image pixel classification errors, soil pixels were counted as vegetation pixels, which produced an overestimation of the canopy temperature under

the developing vegetation abundance. Alternatively, ignoring atmospheric upwelling radiation and transmittance could have produced the uncertainties in the estimated temperatures. In addition, the estimated uncertainty of the incoming short- and long-wave radiation transmittances through the canopy may be another source of Rn estimation errors.

The statistical analysis (see Table I) indicated that the mean measured H was $44 \text{ W} \cdot \text{m}^{-2}$ during the selected days and exhibited a strong daytime variability, with SD of $50 \text{ W} \cdot \text{m}^{-2}$. The low sensible heat fluxes of the soil and canopy were due to the wet surface soil under the canopy and dense vegetation coverage in the study area. Because the study area was located in irrigated farmland with four irrigation times during the crop growing season, the field surface SM was maintained at a high level. Given that the resistance networks of the TSEB model exhibited a better capacity for estimating low H than higher H values [8], the model was successful at calculating H in the irrigated farmlands [see Fig. 3(b)]. The mean bias/RMSE were $5/19 \text{ W} \cdot \text{m}^{-2}$; however, the MAPE was slightly higher (33%). The higher uncertainty of H estimation is not only caused by the uncertainty of the TSEB model but also due to the increased uncertainty of the EC system, which is 18% when the mean H is small in the irrigated farmland [21].

Under high evapotranspiration and frequent irrigation but low precipitation conditions, the mean measured LE was $394 \text{ W} \cdot \text{m}^{-2}$, with SD of $139 \text{ W} \cdot \text{m}^{-2}$ during daytime. Under these conditions, the estimated LE data were relatively scattered compared with the measurements [see Fig. 3(c)]; the mean bias/RMSE was $31/61 \text{ W} \cdot \text{m}^{-2}$. Moreover, Fig. 3(c) exhibits slightly more scatter. However, the low MAPE of 15% demonstrated that the TSEB model performed fairly well. There was an overestimation tendency for LE from the TSEB model compared with that from the EC system. As previously indicated in this study, the overestimation may be partially related to an undermeasurement problem in the EC system. In addition, the measurement uncertainty with 16% for the EC system in the study area can also affect the evaluation of the TSEB model [21].

The previous sensitivity studies found that the TSEB model performance is mainly affected by the uncertainty in surface-air temperature difference [3], [22]. Sometimes, this difference is

dominant due to the errors in determining the surface soil and vegetation component temperatures from the surface composite radiometric temperature. In this letter, it is shown that there is an overestimation of the component temperatures compared with the observed composite radiometric. This often leads to the most crucial effect on the TSEB model performance. In addition, another factor is the strong advective environment in this region. The ground measurements and estimated H were often rather small and instances when H was even negative (H directed toward the surface). However, the sensitivity analysis for the effects of advection on the TSEB model performance is beyond the scope of this letter.

IV. CONCLUSION

Our results demonstrated that the TSEB model using soil and canopy component radiometric temperatures, which were obtained from a high-precision thermal infrared camera, can be applied in a strongly advection-irrigated agricultural area. Notably, the results illustrated that the latent fluxes of the soil and vegetation components were successfully separated with reasonable accuracy, as assessed using ground-based measurements. The estimated $E/ET\%$ and $E/ET\%$ values agreed well with the values observed using the stable oxygen and hydrogen isotopes technique during the early, middle, and late growing seasons. In addition, the TSEB model produced reliable estimations of R_n , H , and LE ; the mean biases of R_n , H , and LE were -18 , 5 , and $31 \text{ W} \cdot \text{m}^{-2}$, respectively, and the RMSEs of R_n , H , and LE were 29 , 19 , and $61 \text{ W} \cdot \text{m}^{-2}$, respectively. This finding suggests that given accurate soil and vegetation component temperatures, E and T can be accurately separated from ET using the TSEB model. In addition, the successful evaluation of the estimated $E/ET\%$ and $E/ET\%$ values based on the application of ground-based measurements demonstrated that the stable oxygen and hydrogen isotopes technique can be applied in separating evapotranspiration validations not only on the field scale but also on the satellite pixel scale, if more observations allowed. Finally, the separate validation approach could be helpful for TSEB model improvements.

ACKNOWLEDGMENT

The authors would like to thank all the scientists, engineers, and students who participated in HiWATER field campaigns. The authors particularly would like to thank Prof. G. Qiu at the School of Environment and Energy, Shengzhen Graduate School, Peking University, for thermal images collection.

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