

Comparison of the Three-Temperature Model and Conventional Models for Estimating Transpiration

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Abstract

The three-temperature (3T) model is used for estimating transpiration from only temperature and net radiation. Comparison with data from a weighing lysimeter showed that the 3T model is accurate. The objectives of this study were to confirm the main advantages, possible field applications, and accuracy of the 3T model over conventional models through theoretical analysis and experimental verification. Four commonly used transpiration models were chosen for comparison: Penman–Monteith (P–M), Bowen ratio, temperature difference, and ENWATBAL models. In a verification experiment conducted in a 1-ha sorghum field, microclimate, soil, and plant variables were extensively measured. The results showed that the 3T model has 4 main advantages. The major advantage is that it is theoretically sound, simple, and easily applicable, especially in developing countries. The next advantage is that aerodynamic resistance, surface resistance, and empirical parameters are not included. As a result, the transpiration process can be more easily revealed. The third advantage is that quantitative information on transpiration can be obtained with considerably fewer measurements, especially for application to remote sensing. The fourth advantage is that there is no fetch requirement. Because of these advantages, the 3T model could be applied both at small heterogeneous sites for local measurements and in large-scale fields for remote sensing. The transpiration estimated by the 3T model and the 4 conventional models was compared with lysimeter-measured data. The transpiration estimated by the 3T and P–M models agreed with the lysimeter-measured values. The mean absolute errors (*MAE*) between the measured value and the value obtained by the 3T model and between the measured value and that obtained by the P–M model were 0.45 and 0.42 mm d⁻¹, respectively. The *MAE* between the measured value and that obtained by the Bowen ratio model was 0.63 mm d⁻¹, between the measured value and that obtained by the temperature difference model, 0.69 mm d⁻¹, and between the measured value and that obtained by the ENWATBAL model, 0.88 mm d⁻¹. These results show that the *MAE* values of all the 5 models were < 1 mm d⁻¹, and the performance of the 3T model was as good as that of the conventional models.

Discipline: Agro-meteorology

Additional key words: three-temperature model, transpiration, mean absolute error, Penman–Monteith, Bowen ratio, temperature difference, ENWATBAL

Introduction

Micrometeorological models are widely used for the estimation of evapotranspiration (*ET*). These models

enable to deduce *ET* from meteorological variables (e.g. temperature, humidity, wind velocity, radiation) measured at or above an evaporative surface. In principle, the models are aimed at estimating natural *ET* with minimal disturbance to the microclimate. The temperature differ-

This work was partially financed by NKBRFS Project G2000018604.

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Received 11 May 2001; accepted 26 November 2001.

ence model is one of the commonly used micrometeorological models. According to this model, ET is given as:

$$ET = (R_n - G) - \rho C_p \frac{T_s - T_a}{r_a} \quad (1)$$

where R_n is the net radiation of the canopy (W m^{-2}), G is the heat flux to soil (W m^{-2}), ρ is the air density (1.2 kg m^{-3}), C_p is the specific heat of air ($1,010 \text{ J kg}^{-1} \text{ }^\circ\text{C}^{-1}$), r_a is the aerodynamic resistance (s m^{-1}), and T_s and T_a are the temperatures of the canopy surface and air, respectively. In Eq. (1), in addition to $R_n - G$, r_a , T_s , and T_a are required. The surface temperature can be acquired through the use of infrared radiometry from above, or through the integrated foliage temperature. This model has so far been used mainly for simple surfaces^{9–11,19,30,31}. However, as infrared thermometers and thermal graphic technologies improve, this technique could be applied to remote sensing.

By introducing an imitation leaf (a leaf without transpiration), Qiu et al.^{22,26} further improved the model for the estimation of transpiration. The proposed equation is:

$$T = R_n - R_{np} \frac{T_s - T_a}{T_p - T_a} \quad (2)$$

where T is the transpiration rate from the plant canopy (W m^{-2}), R_{np} is the net radiation at the imitation leaf (W m^{-2}), and T_p is the temperature of the imitation leaf. Because 3 temperatures (T_c , T_a , T_p) are involved, for convenience, Eq. (2) is hereafter referred to as the three-temperature model or the 3T model. Comparison with data from a weighing lysimeter showed that the 3T model could be used as an accurate method for estimating transpiration^{22,26}.

Because the 3T model is relatively new, it has not been compared with other conventional models. Hence the following questions are raised: What is the accuracy of the 3T model compared with other conventional models? What are the main advantages of the 3T model over the others? What are the possible applications of the 3T model? The objectives of this study were to answer these questions through theoretical analysis and experimental verification. Four commonly used evapotranspiration models were chosen for comparison: Penman–Monteith (P–M), Bowen ratio, temperature difference, and ENWATBAL.

Materials and methods

Experimental field

Verification experiments were conducted in a 1-ha, nearly level (< 0.1% slope) field with a texture of 95.8% coarse sand (0.25–2.00 mm range) located at the Arid

Land Research Center, Tottori University, Japan (15 m above sea level, 35°32'N). The groundwater table at the site is deeper than 5 m. Soil in this field can be divided into 2 layers, 5–10 cm deep and 10–300 cm deep. The field capacity and permanent wilting point of the second layer are $0.074 \text{ m}^3 \text{ m}^{-3}$ and $0.022 \text{ m}^3 \text{ m}^{-3}$, respectively. The saturated hydraulic conductivity is $2.66 \times 10^{-4} \text{ m s}^{-1}$.

The experiment was conducted in August 1994 in a grain sorghum crop (*Sorghum bicolor* (L.) Moench.) field. Sorghum was sown on June 10, 1994 at a row spacing of 0.60 m. The density was approximately 8 plants m^{-2} . Because the soil surface was fully covered by the sorghum canopy from early August, data collected during August 10–18 and 24–31 were used for the analysis (data for August 19–23 were not included because of heavy rain and electrical problems).

Evapotranspiration

Actual evapotranspiration was measured with a weighing lysimeter (1.5 m wide by 1.5 m deep), which was installed in the center of the field. This weighing lysimeter had a resolution of 50 g, corresponding to 0.028 mm of water depth. The sampling interval was 15 s; 120 instantaneous values were measured, and the average value was recorded every 30 min. Daily soil evaporation below the canopy was measured with microlysimeters (3 replications), 153 mm long by 50 mm wide. The microlysimeters were prepared by taping 3 standard soil sample containers together. Their volume was 300 cm^3 .

Temperatures

Imitation leaf temperature, foliage temperature, and air temperature were measured with a thermocouple in 3 replicates every 5 min. These 3 temperatures were measured just above the canopy at exactly the same location. The temperatures were recorded on 2 dataloggers. The temperatures of both the adaxial and abaxial surfaces were measured. Information on the measurement of the temperatures is described in Qiu²² and Qiu et al.^{23,26}.

Crop-related variables

The plant leaf area was measured with a leaf area meter (AAC-400, Hayashi Electric Co., Ltd., Tokyo, Japan) weekly throughout the experimental period to calculate the leaf area index (LAI). The LAI was > 3 and the field was fully covered by the canopy¹³.

Root samples were taken at a distance of 30 cm from the plant (middle of crop rows), 15 cm from the plant, and under the plant, all in the main root zone at a 5 cm depth. Root length, root surface area, and root volume were estimated with a Deperos System Root Analyzer (JX-450, Sharp Co., Ltd., Tokyo, Japan). Stomatal resis-

tance was measured with a LI-1600 Steady State Porometer (Li-Cor. Inc., Lincoln, USA).

Soil-related variables

Soil temperature was measured with a thermocouple (copper–constant, Type T, 0.32 mm diam.) at depths of 2, 4, 6, 8, 10, 15, 20, 50, and 100 cm below the surface. Soil water pF was measured with Zest DDS1 tensiometers (Zest Inc., Yokohama, Japan) at depths of 10, 15, 30, 50, 70, and 100 cm. Soil temperature and tensiometer data were recorded every 10 min with DL-350 dataloggers (Teac Co., Ltd., Tokyo, Japan). Soil water content was measured gravimetrically every day (2 replications) at depths of 5, 10, 15, 20, 25, and 30 cm.

Meteorological variables

The weather parameters used in the 4 conventional models were measured in the sorghum field. Net radiation, soil heat flux, air temperature, relative humidity, and wind speed were measured every 20 s, and average values were automatically recorded in the dataloggers every 15 min. Air temperature and humidity were also measured at heights of 190, 170, 150, 130, 120, and 110 cm. Weather parameters were measured at a standard meteorological station (Ogasawara Co., Ltd., Tokyo, Japan) 300 m from the field. The variables measured at this station included the wind speed and direction, air temperature and humidity, precipitation, solar irradiance, sunshine hours, pan evaporation, and soil temperatures at depths of 10, 30, and 50 cm. The sampling interval for pan evaporation was 1 min. The sampling interval for all the other measurements was 10 s.

Results and discussion

Model evaluation

Several evaluation criteria could be used to test the performance of the models. Fox⁷ identified 2 general types of quantitative measures: measures of correlation and measures of difference. The regression coefficient has been widely used as a quantitative index of correlation between measured and calculated values. Willmott³⁴ recommended the use of the mean absolute error (MAE) as a better measure of difference. Therefore, in this study the MAE was used to evaluate the accuracy of the models. MAE is defined⁶ as:

$$MAE = \frac{1}{N} \sum_{i=1}^N |S_i - M_i| \quad (3)$$

where S_i and M_i are the paired calculated and measured values, respectively, and N is the total number of observations. Measured transpiration was obtained from lysime-

ter-measured ET minus microlysimeter-measured soil evaporation E . The transpiration estimated by the 3T model was obtained by the procedures described in Qiu et al.²⁶. The procedures for estimating transpiration by the other models will be described in the following sections. In our analysis, daytime transpiration was used for the P–M, Bowen ratio, and temperature difference models. The 24-h transpiration was used for ENWATBAL.

Comparison with P–M model

Combination methods are commonly used to estimate ET . These methods involve a combination of energy balance and aerodynamic transport of water vapor. Such equations for potential ET include the Penman equation²¹, modified Penman equation³², and P–M equation¹⁸. For an unsaturated surface, surface (or canopy) resistance is introduced^{18,29}. The P–M equation can be expressed as:

$$ET = \frac{\Delta(R_n - G) + \rho C_p(e_s - e_a)/r_a}{\Delta + \gamma(1 + r_c/r_a)} \quad (4)$$

where e_s is the saturated vapor pressure at air temperature (Pa), e_a is the air vapor pressure (Pa), Δ is the slope of the saturation vapor pressure–temperature curve at the mean temperature (Pa °C⁻¹), γ is the psychrometric constant (66 Pa °C⁻¹), r_c is the canopy resistance (s m⁻¹), and r_a is the aerodynamic resistance (s m⁻¹).

It should be mentioned that the simplification achieved by the elimination of the surface temperature in the P–M equation requires the determination of the surface resistance, which in turn has to be estimated from the stomatal resistance and leaf area index.

Usually r_a is estimated from the wind speed. Jackson et al.¹² suggested that r_a could be expressed as:

$$r_a = \frac{4.72 \left(\ln \frac{z-d}{z_0} \right)^2}{1 + 0.54U} \quad (5)$$

where z is the height at which the wind speed is measured (m), d is the zero-plane displacement (m), z_0 is the roughness length (m), and U is the wind speed at z height (m s⁻¹). For a fully covered plant community, the empirical relationships of $z_0 = 0.13h$ and $d = 0.63h$ can be used, where h is the height of the crop expressed in meters (Monteith, 1965). Δ (Pa °C⁻¹) can be estimated as:

$$\Delta = \frac{2502992.1}{(T_a + 237.3)^2} \exp\left(\frac{17.3T_a}{T_a + 237.3}\right) \quad (6)$$

e_s (Pa) can be calculated³ as:

$$e_s = 610.8 \exp\left(\frac{17.3T_a}{T_a + 237.3}\right) \quad (7)$$

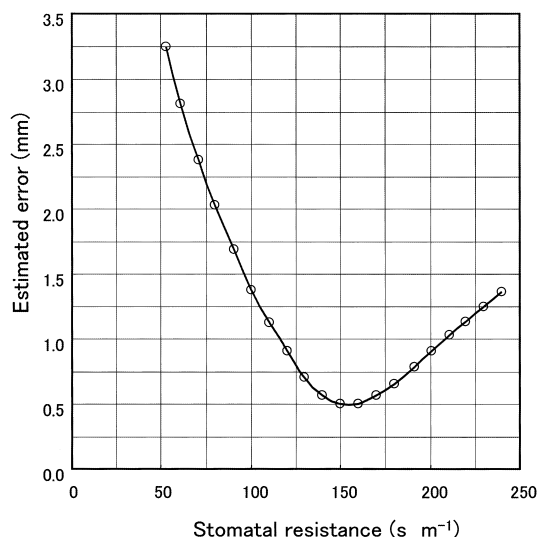


Fig. 1. Errors of estimated transpiration by Penman–Monteith model for different stomatal resistance values

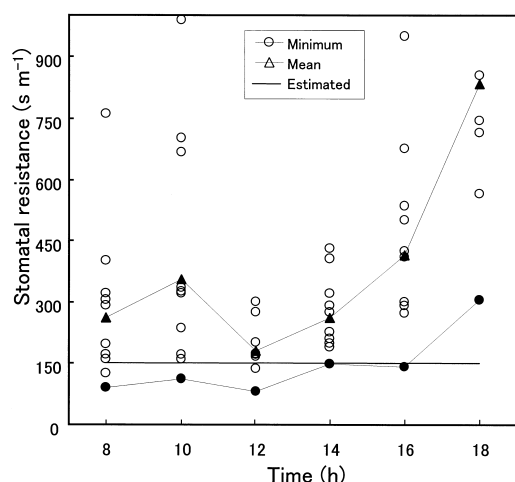


Fig. 2. Stomatal resistance of sorghum leaves measured with a porometer

$$e_a = e_s \times \frac{RH}{100} \tag{8}$$

where RH is the relative humidity of air.

In the P–M model, besides r_a , r_c is also required. Because of the variation of r_c with plant species, location, and time, it is always difficult to find a suitable r_c value for the P–M model. Empirical equations enable to estimate the canopy resistance from the leaf area index (LAI) and minimum stomatal resistance (r_s), such as $r_c = r_s / (LAI/2)$. Usually $r_s = 100 \text{ s m}^{-1}$ is considered to be a suitable value¹³.

By using different values of r_s in the P–M equation and comparing the calculated ET with lysimeter-measured values, we found that $r_s = 150 \text{ s m}^{-1}$ is a suitable value (Fig. 1). Fig. 1 shows that the P–M model is sensitive to stomatal resistance. For example, if $r_s = 100 \text{ s m}^{-1}$ is selected, the error increases significantly. Fig. 2 shows the stomatal resistance measured with a porometer. The minimum values of the measured r_s ranged from 75 to 300 s m^{-1} . The estimated value of $r_s = 150 \text{ s m}^{-1}$ was in this range.

The input variables and the main characteristics of the 3T and P–M models are summarized in Table 1. The 3T model has 3 advantages over the P–M model. First, r_a and r_c are not required. This is important, because accurate estimates of r_a and r_c are the major difficulty in determining ET for many applications. Second, fewer variables are included: 2 in the 3T model versus 6 in the P–M model. Third, measurement and analysis of the parameters involved are relatively easy.

Fig. 3 shows a comparison of the daily T values measured with the lysimeter, and daily T values estimated by the 3T and P–M models. The estimated T value by the P–M equation is equal to $ET - E$, where ET is calculated from Eq. (4) and E is measured with a microlysimeter. Fig. 3a shows that the daily T values estimated by the 3T and P–M models agreed with the lysimeter-measured values. Most of the values were in the range of 4–7 mm, and all the points were near the 1:1 line. Fig. 3b shows the cumulative T values given by the lysimeter, P–M and 3T

Table 1. Comparison of data requirements and applicability of the 3T and Penman–Monteith models

	3T model	P–M model
Data requirement	Temperature Net radiation	Net radiation Soil heat flux Humidity Temperature r_a r_c
Applicability	Both large, uniform sites and small, heterogeneous sites	Large, uniform fields only

models over the 17-day period, namely 80.31, 80.05, and 80.10 mm, respectively. The difference between the lysimeter and P-M values was 0.26 mm, and the difference between the lysimeter and 3T values was 0.21 mm. These results show that the values obtained by both the P-M and 3T models agreed well with those measured with the lysimeter.

The MAE between T measured with the lysimeter and estimated by P-M was 0.42 mm d^{-1} . The MAE between T measured with the lysimeter and estimated by 3T was 0.45 mm d^{-1} . These results suggest that, although the performance of the 2 models is good, the P-M model performs slightly better than the 3T model. However, as previously indicated, because the canopy resistance in the P-M equation was calibrated from the lysimeter values,

the results from the P-M model should agree with the results from the lysimeter. Therefore, we concluded that the accuracy of the 3T model is at least as high as that of the P-M model.

Comparison with Bowen ratio model

The use of the Bowen ratio model is a well-known approach for estimating ET . The general form of the Bowen ratio method is given in Eqs. (9) and (10). The Bowen ratio (β) is defined as the ratio of sensible to latent heat flux, and can be expressed² as:

$$\beta = (C_p/L) \frac{\Delta T}{\Delta q} \tag{9}$$

where ΔT and Δq are the temperature and humidity gradi-

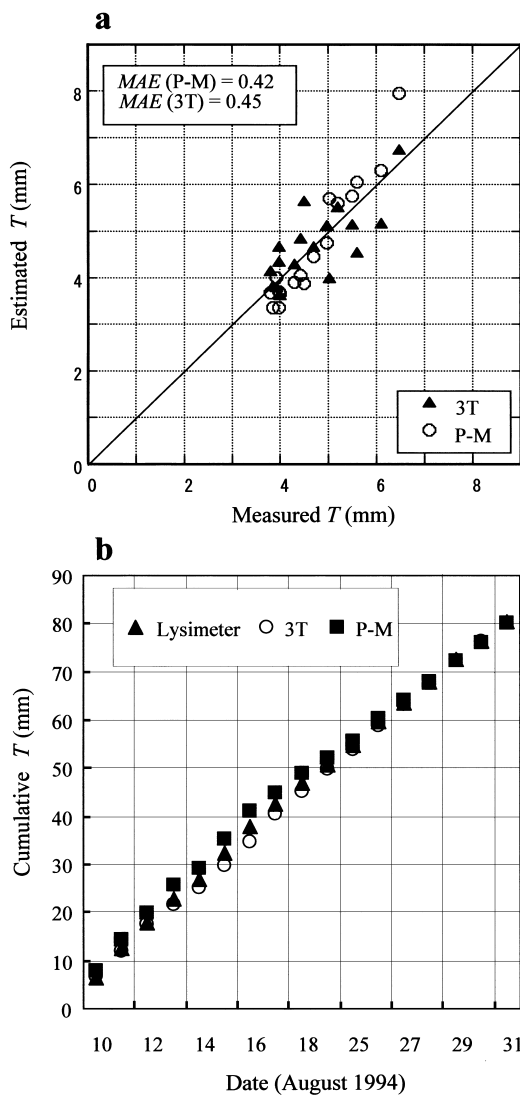


Fig. 3. Comparison of transpiration values measured with a lysimeter, estimated by the P-M model, and estimated by the 3T model
a: Daily transpiration, b: Cumulative transpiration.

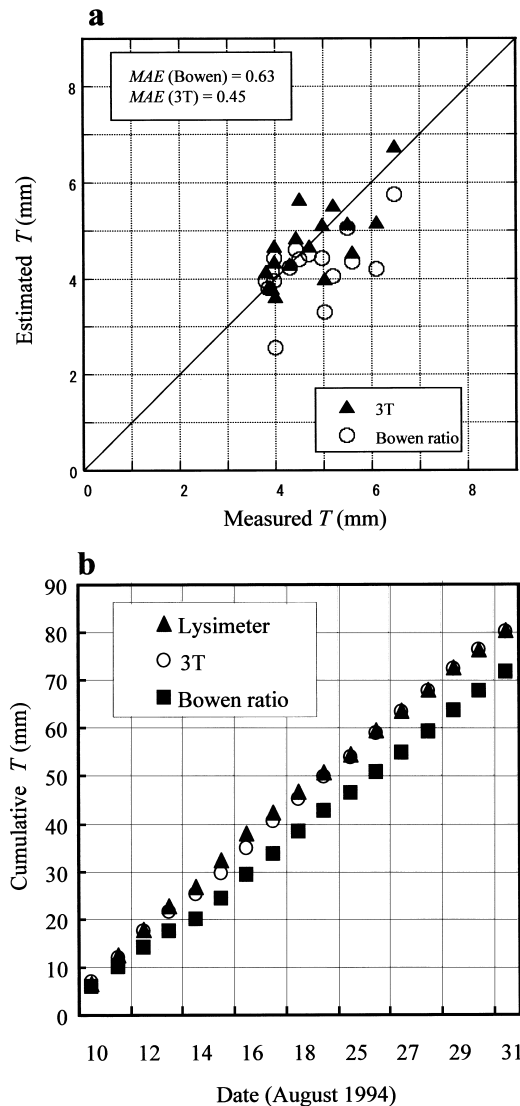


Fig. 4. Comparison of transpiration values measured with a lysimeter, estimated by the Bowen ratio model, and estimated by the 3T model
a: Daily transpiration, b: Cumulative transpiration.

ents over the same height interval, and L is the latent heat of vaporization (2.4 MJ kg^{-1}). ET is given by:

$$ET = \frac{R_n - G}{1 + \beta} \quad (10)$$

In the Bowen ratio model, net radiation, soil heat flux, and temperature and humidity gradients are required. However, measurements of ΔT and Δq close to the surface are desirable, because they minimize the effect of buoyancy and advection. However, measurements made too close to the surface are likely to be affected by the low surface homogeneity, particularly in the case of tall vegetation^{1,31}.

Fig. 4 shows a comparison of the T values estimated by the Bowen ratio and 3T models. The T values estimated by the Bowen ratio model were equal to $ET - E$, where ET is calculated from Eq. (10) and E is measured with the microlysimeter. Generally, the values of T estimated by both the Bowen ratio and 3T models agreed with the lysimeter-measured values. The MAE between the measured T and the Bowen ratio model-estimated T was 0.63 mm d^{-1} . The MAE between the measured T and the 3T-model-estimated T was 0.45 mm d^{-1} . However, the estimated results of the 3T model were closer to the 1:1 line than those of the Bowen ratio model; the Bowen ratio model slightly underestimated the daily T values (Fig. 4a). This underestimation of the T values is further shown in Fig. 4b. The cumulative T values were 80.31, 80.10, and 71.62 mm for the lysimeter, 3T, and Bowen ratio models, respectively. The difference between the values obtained by the lysimeter and the Bowen ratio model was 8.69 mm, which is larger than that between the values determined with the lysimeter and by the 3T model (0.21 mm). The reason for this underestimation is not clear. The error measurements of ΔT and Δq close to the surface may account for the possible source of error. These results show that the T values estimated by the 3T model agreed with the lysimeter-measured T values better than those estimated by the Bowen ratio model. Hence, we can conclude that the 3T model performs better than the Bowen ratio model.

Comparison with the temperature difference model

Evapotranspiration flux according to this method is given by Eq. (1). In addition to $R_n - G$, aerodynamic resistance (r_a), surface temperature, and air temperature are required. Fig. 5 shows a comparison between the 3T and temperature difference models. The T values estimated by the temperature difference model are equal to $ET - E$, where ET is calculated from Eq. (1) and E is measured with the microlysimeter. Experimental results show that the performance of the 3T model can be as

good as that of the temperature difference model. The MAE between the measurements and the temperature difference model was 0.69 mm d^{-1} . The MAE between the measurement and the 3T model was 0.45 mm d^{-1} .

Fig. 5a shows that the daily T values estimated by the temperature difference and 3T models agreed with the lysimeter-measured values. Most of the values were in the range of 4–7 mm, and all the points were close to the 1:1 line. Fig. 5b shows a comparison of the cumulative T values obtained with the lysimeter and the 3T and temperature difference models over a period of 17 d. The cumulative values of T were 80.31, 80.10, and 83.08 mm for the lysimeter, 3T, and temperature difference model,

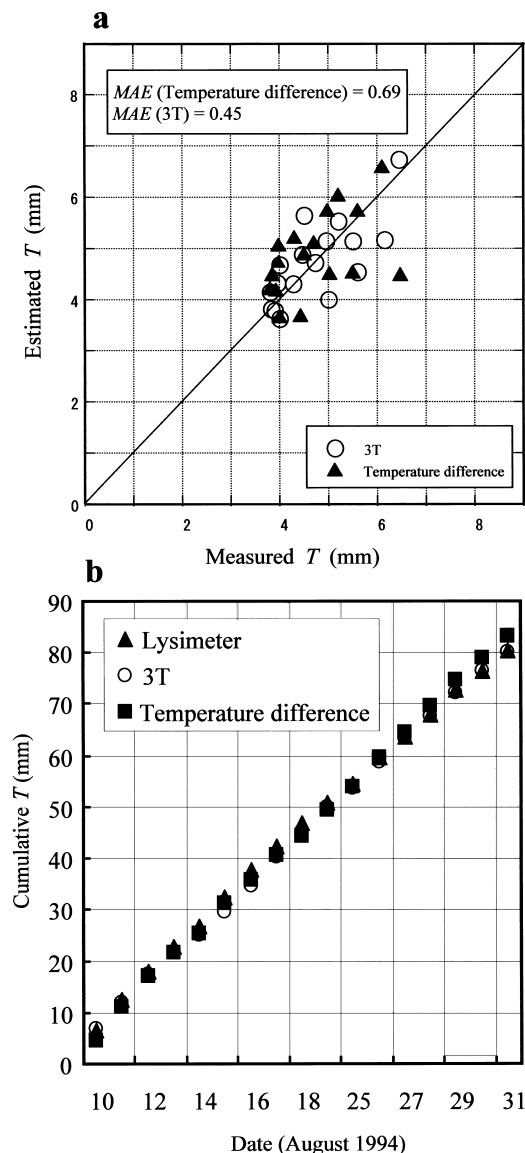


Fig. 5. Comparison of transpiration values measured with a lysimeter, estimated by the temperature difference model, and estimated by the 3T model
 a: Daily transpiration, b: Cumulative transpiration.

respectively. The difference between the values obtained with the lysimeter and by the 3T model was 0.21 mm, and the difference between those obtained with the lysimeter and by temperature difference model was 2.77 mm. These results show that the values obtained by both the 3T and temperature difference models agreed very well with the lysimeter values.

Comparison with ENWATBAL model

ENWATBAL (ENergy and WATER BALance), a mechanistic *ET* model, can separate the calculation of *E* and *T* as a function of crop development, changes in soil water reserves, and weather¹⁷. ENWATBAL also estimates other parameters of interest, such as soil moisture and temperature profiles, soil surface and crop canopy temperature, soil and crop water potential, soil heat flux, and net irradiance below and above the crop.

The ENWATBAL model was first proposed by Lascano et al.¹⁷ and was derived from the combination of 3

different models: Conservb^{15,16}, Watbal³³, and Microweather^{5,8}. Compared with many other models, ENWATBAL has 2 advantages. First, the water and energy balances for both canopy and soil surface are simulated. Second, the energy and water balances of the entire soil profile are calculated separately from those of the plant canopy. Thus, soil evaporation and plant transpiration are calculated separately. As an example, the variables required by ENWATBAL are given in Table 2. Besides these weather variables, ENWATBAL also requires initial and boundary conditions. ENWATBAL was found to be a useful tool for separately estimating soil evaporation and plant transpiration in the same experimental field as in the case of this study²⁷.

Fig. 6a shows a comparison of the *T* values measured with the lysimeter and simulated daily (24 h) by ENWATBAL. Most of the simulated *T* values were below the 1:1 line and ENWATBAL slightly underestimated daily *T*. Fig. 6b shows that the cumulative *T* val-

Table 2. Weather variables used as inputs for ENWATBAL

DOY	R_s (MJ m ⁻²)	T_a Max (°C)	T_a Min (°C)	T_{dp} Max (°C)	T_{dp} Min (°C)	U (m s ⁻¹)	LAI	Root depth (m)	R_{max} (m)	Air pressure (kPa)
220	22.13	33.0	24.8	25.4	22.1	1.41	3.90	1.05	0.15	101.28
221	18.14	33.7	23.5	26.2	21.4	1.80	3.75	1.05	0.16	101.28
222	22.84	38.5	23.5	22.4	19.8	2.24	3.60	1.05	0.16	101.28
223	22.29	37.6	25.6	22.8	20.9	2.02	3.45	1.05	0.17	101.28
224	19.96	39.2	22.9	25.5	19.5	1.53	3.30	1.08	0.17	101.28
225	15.57	37.2	23.8	23.4	19.8	1.69	3.15	1.08	0.17	101.28
226	13.89	34.6	26.9	24.5	21.6	3.06	3.00	1.11	0.17	101.28
227	22.24	39.3	27.2	22.6	17.0	2.34	2.85	1.11	0.17	101.28
228	23.62	36.8	24.4	24.3	18.6	2.41	2.80	1.14	0.18	101.28
229	23.14	34.2	23.4	24.0	18.9	1.72	2.75	1.14	0.18	101.28
230	22.71	33.8	23.0	24.6	19.8	1.78	2.70	1.17	0.18	101.28
231	16.29	31.7	22.3	23.4	19.2	1.56	2.65	1.17	0.18	101.28
232	18.28	31.5	23.2	23.3	19.3	1.36	2.60	1.20	0.18	101.28
233	12.08	30.5	22.0	23.3	20.5	1.81	2.55	1.20	0.19	101.28
234	15.69	30.4	26.1	23.8	22.0	2.18	2.50	1.23	0.19	101.28
235	21.46	30.6	20.6	21.8	17.0	1.44	2.49	1.23	0.19	101.28
236	22.29	31.2	19.9	23.1	18.2	1.64	2.49	1.26	0.19	101.28
237	19.68	33.4	22.6	23.9	20.6	1.66	2.48	1.26	0.19	101.28
238	19.42	36.6	24.7	24.6	20.1	2.22	2.48	1.29	0.20	101.28
239	17.73	34.1	25.0	24.4	21.3	1.91	2.47	1.29	0.20	101.28
240	19.72	34.1	24.1	24.6	20.1	1.65	2.47	1.32	0.20	101.28
241	21.07	33.7	24.0	23.5	20.0	1.34	2.46	1.32	0.20	101.28
242	20.09	33.5	23.9	24.9	21.6	1.24	2.45	1.35	0.20	101.28
243	20.38	33.9	23.5	24.6	21.4	1.34	2.45	1.35	0.20	101.28

Data from a sorghum field in August 1994 are shown as an example. DOY: Day of year (for example, DOY 220 corresponds to 8 August), R_s : Solar radiation, T_a : Air temperature, T_{dp} : Dew point temperature, U : Wind speed, LAI : Leaf area index, R_{max} : Depth of maximum relative root density.

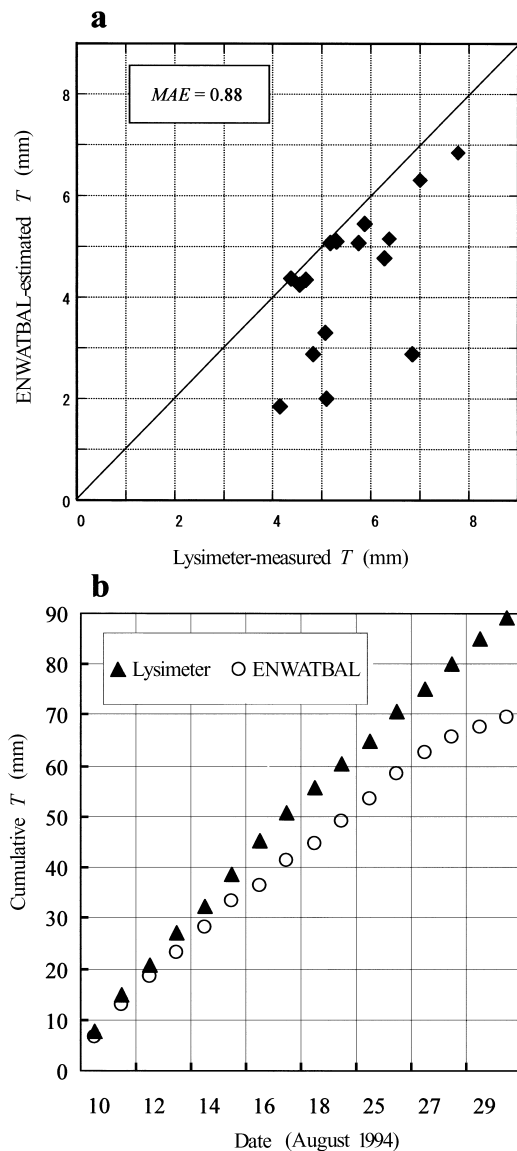


Fig. 6. Comparison of transpiration values measured with a lysimeter, estimated by the ENWATBAL model, and estimated by the 3T model

a: Daily transpiration, b: Cumulative transpiration.

ues obtained with the lysimeter and by ENWATBAL over a period of 16 d were 89.19 and 69.51 mm, respectively. The difference between the values obtained with the lysimeter and by ENWATBAL was 19.68 mm. The MAE between the measured values and those obtained by ENWATBAL was 0.88 mm d^{-1} . This value was about twice as large as that given by the 3T model. These results show that the performance of the 3T model is better than that of ENWATBAL.

In ENWATBAL, T is calculated from an energy balance approach, which is closely related to the canopy resistance and stomatal resistance. The relation between

the stomatal conductance and leaf water potential and the relation between the stomatal conductance and solar irradiance are applied as initial conditions. The empirical nature of these relations may be a source of error, causing an underestimation in the calculation of T . The underestimation of T demonstrates the need for a better mechanistic simulation of these processes.

Potential applicability

Comparison with conventional methods shows that the use of the 3T model is a simple and accurate method for estimating plant transpiration. These advantages make the 3T model widely applicable under various conditions.

1. Remote sensing technology

Estimation of ET from remotely sensed observations has several advantages over other methods^{4,20}. In the 3T model, the required data are the net radiation and temperature only. These variables are easily gathered by remote sensing. As an extension of the 3T model, soil evaporation was successfully estimated by using temperatures remotely measured with infrared thermometers^{24,25}.

The temperature term in Eq. (2) is defined as the plant transpiration transfer coefficient (h_{at}), which can be expressed²⁸ as:

$$h_{at} = \frac{T_c - T_a}{T_p - T_a} \quad (11)$$

Theoretically, $h_{at} \leq 1$. If $T_c = T_p$, h_{at} is assumed to be the maximum value ($h_{at} = 1$) and transpiration the minimum value ($T = 0$). This limit is determined by the lack of water for transpiration. On the other hand, when h_{at} has a minimum value, transpiration can reach a maximum value (potential transpiration rate). This limit is determined by the available energy for transpiration. Therefore, h_{at} can determine the transpiration rate from the minimum value to the maximum value. A lower value of h_{at} corresponds to a higher transpiration rate. In Eq. (2), because R_n , R_{np} , and $(T_p - T_a)$ are determined only by the physical environment, the transpiration properties of the plant itself are determined by $(T_c - T_a)$. Under the same physical conditions, the differences in the transpiration properties of different species are indicated by $(T_c - T_a)$.

After the tests were performed in a large uniform field, a greenhouse, and a growth chamber, h_{at} was found to be a useful indicator of the growth and water status of plants²⁸. Because the surface temperature can be easily estimated, h_{at} could be used as an indicator of the growth and water status of vegetation by remote sensing technology.

2. Strong error resistance

Because of the special form of Eq. (2), some system-

atic errors, such as those associated with equipment and method, can be removed. Sensitivity analysis shows that, although the 3 temperatures are the most sensitive input parameters in estimating T , simultaneous changes in them will not cause a significant error in T ²². Errors of 5% in the 3 temperatures will result in changes from -0.17 to $+0.17\%$ in T . Errors of 10% will result in changes from -0.34 to $+0.17\%$ in T . Errors of 15% will result in changes from -0.50 to $+0.51\%$ in T . Errors of 90% will result in changes from -2.81 to $+3.15\%$ in T . Therefore, the 3T method shows a strong error resistance to simultaneous changes in the 3 temperatures. These results were also verified by the extended 3T model²⁴.

A model with a strong error resistance is very important for many studies and applications. For example, in the studies on global warming caused by CO_2 , the possible effect of an elevated CO_2 concentration on net radiation could be around 1% and on ET it could be within 10%¹⁴. These values are in the error ranges for most equipment and methods. For most of the conventional models, more studies are required to obtain satisfactory results. Under these conditions, it will be relatively easy to obtain satisfactory results with the 3T model.

3. Applicable under various conditions

Owing to fetch requirements, most of the conventional models can only be applied to large uniform sites. In the 3T model, because the measurement of net radiation and temperature is not affected by data collection problems, the model can be used in both large flat fields and at small heterogeneous sites, such as in a greenhouse. This technology has been successfully applied to estimate the crop water stress index for greenhouse melon²⁶. Furthermore, h_{at} was successfully evaluated for open-field-grown sorghum, potted tomato (in both growth chamber and greenhouse), and greenhouse melon. Therefore, the 3T model could be used when the use of other conventional models is limited.

Conclusion

There are many conventional models for estimating transpiration. Four of these commonly used models were selected for comparison with the 3T model: P–M, Bowen ratio, temperature difference, and ENWATBAL models. In a comparison conducted in a sorghum field, microclimate variables, soil-related variables, and plant-related variables were extensively measured. The results showed that the 3T model has 4 main advantages. The major advantage is that it is theoretically sound, simple, and applicable, especially in developing countries. The next advantage is that the aerodynamic resistance, surface

resistance, and empirical parameters are not included. As a result, the transpiration process can be more easily revealed. The third advantage is that quantitative information on transpiration can be obtained with considerably fewer measurements, especially for application to remote sensing. The fourth advantage is that there is no fetch requirement. Because of these advantages, the 3T model could be applied both at small heterogeneous sites for local measurements and in large-scale fields for remote sensing.

Transpiration estimated by the 3T model and the other 4 conventional models was compared with lysimeter-measured data. Transpiration estimated by both the 3T and P–M models agreed with the lysimeter-measured values. The MAE between the measured value and that obtained by the 3T model and the MAE between the measured value and that obtained by the P–M model were 0.45 and 0.42 mm d^{-1} , respectively. These results suggest that, although the performance of the 2 models is good, the P–M method performs slightly better than the 3T method. However, because canopy resistance in the P–M equation was calibrated from the lysimeter values, the results from the P–M model should agree with the measured ones. Therefore, we conclude that the accuracy of the 3T model is as high as that of the P–M model. The MAE between the measured value and that obtained by the Bowen ratio model was 0.63 mm d^{-1} , between the measured value and that obtained by the temperature difference model, 0.69 mm d^{-1} , and between the measured value and that obtained by ENWATBAL, 0.88 mm d^{-1} . These results show that the MAE values of all the 5 models were $< 1 \text{ mm d}^{-1}$, and that the performance of the 3T model could be as good as, or better than, that of the conventional models.

References

1. Angus, D. E. & Watts, P. J. (1984): Evapotranspiration—how good is the Bowen-ratio method? *In* Evapotranspiration from Plant Communities. ed. Sharma, M. L., Elsevier, Amsterdam. 133–150.
2. Bowen, I. S. (1926): The ratio of heat losses by conduction and by evaporation from any water surface. *Phys. Rev.*, **27**, 779–789.
3. Burman, R. D., Cuenca, R. H. & Weiss, A. (1983): Techniques for estimating irrigation water requirements. *Adv. Irrig.*, **2**, 335–394.
4. Chanzy, A., Bruckler, L. & Perrier, A. (1995): Soil evaporation monitoring: a possible synergism of microwave and infrared remote sensing. *J. Hydrol.*, **165**, 235–259.
5. Chen, J. (1984): Mathematical analysis and simulation of crop-Micrometeorology. Ph. D. Thesis, Dept. of Theoretical Production Ecology, Agric. Univ., Wageningen, the Netherlands.

6. Durar, A. A. et al. (1995): Measured and simulated surface soil drying. *Agron. J.*, **87**, 235–244.
7. Fox, D. G. (1981): Judging air quality model performance; a summary of the AMS workshop on dispersion model performance, Woods Hole, MA. 8–11 Sept. 1980. *Bull. Am. Meteorol. Soc.*, **62**, 599–60.
8. Goudriaan, J. (1977): Crop micrometeorology; a simulation study. Pudoc, Wageningen, the Netherlands, pp. 257.
9. Hatfield, J. L. (1985): Wheat canopy resistance determined by energy balance techniques. *Agron. J.*, **77**, 279–283.
10. Idso, S. B., Reginato, R. J. & Jackson, R. D. (1977): An equation for potential evaporation from soil, water and crop surfaces adaptable to use by remote sensing. *Geophys. Res. Lett.*, **4**, 187–188.
11. Jackson, R. D., Reginato, R. J. & Idso, S. B. (1977): Wheat canopy temperature: a practical tool for evaluating water requirements. *Water Resour. Res.*, **13**, 651–656.
12. Jackson, R. D. et al. (1982): Canopy temperature as a crop water stress indicator. *Water Resour. Res.*, **17**, 1133–1138.
13. Jensen, M. E., Burman, R. D. & Allen, R. G. (1990): Evapotranspiration and irrigation water requirements. In ASCE manuals and reports on engineering practice, No. 70. New York, 25–41.
14. Kimball, B. A. et al. (1999): Free-air CO₂ enrichment and soil nitrogen effects on energy balance and evapotranspiration of wheat. *Water Resour. Res.*, **35**, 1179–1190.
15. Lascano, R. J. & van Bavel, C. H. M. (1983): Experimental verification of a model to predict soil moisture and temperature profiles. *Soil Sci. Soc. Am. J.*, **47**, 441–448.
16. Lascano, R. J. & van Bavel, C. H. M. (1986): Simulation and measurement of evaporation from a bare soil. *Soil Sci. Soc. Am. J.*, **50**, 1127–1132.
17. Lascano, R. J. et al. (1987): Energy and water balance of sparse crop; simulated and measured soil and crop evaporation. *Soil Sci. Soc. Am. J.*, **51**, 1113–1121.
18. Monteith, J. L. (1965): Evaporation and environment. *Symp. Soc. Exp. Biol.*, **19**, 205–234.
19. Monteith, J. L. (1981): Evaporation and surface temperature. *Q. J. Roy. Meteorol. Soc.*, **107**, 1–27.
20. Otle, C. & Vidal-Madjar, D. (1994): Assimilation of soil moisture inferred from infrared remote sensing in a hydrological model over the HAPEX-MOBILHY region. *J. Hydrol.*, **158**, 241–264.
21. Penman, H. L. (1948): Natural evaporation from open water, bare soil and grass. *Proc. Roy. Soc. Ser. A*. No. 1032, **193**, 120–145.
22. Qiu, G. Y. (1996): A new method for estimation of evapotranspiration. Doctoral dissertation, the United Graduate School of Agriculture Science, Tottori University, Japan.
23. Qiu, G. Y., Momii, K. & Yano, T. (1996): Estimation of plant transpiration by imitation leaf temperature I. Theoretical consideration and field verification. *Trans. Jpn. Soc. Irrig., Drain. Reclam. Eng.*, **64**, 401–410.
24. Qiu, G. Y., Yano, T. & Momii, K. (1998): An improved methodology to measure evaporation from bare soil based on comparison of surface temperature with a dry soil. *J. Hydrol.*, **210**, 93–105.
25. Qiu, G. Y. et al. (1999a): Estimation of soil evaporation using the differential temperature method. *Soil Sci. Soc. Am. J.*, **63**, 1608–1614.
26. Qiu, G. Y. et al. (2000): Detection of crop transpiration and water stress by temperature related approach under the field and greenhouse conditions. *JARQ*, **34**, 29–37.
27. Qiu, G. Y. et al. (1999b): Experimental verification of a mechanistic model to partition evapotranspiration into soil water and plant evaporation. *Agric. For. Meteorol.*, **93**, 79–93.
28. Qiu, G. Y., et al. (2002): Acoustic emissions in tomato plants under water stress conditions. *JARQ*, **36**, 103–109.
29. Rijtema, P. E. (1966): Evapotranspiration. *Tech. Bull. I. C. W.*, **47**, 89.
30. Stone, L. R. & Horton, M. L. (1974): Estimating evapotranspiration using canopy temperatures: field evaluation. *Agron. J.*, **66**, 540–545.
31. Tanner, C. B. & Fuchs, M. (1968): Evaporation from unsaturated surface: a generalized combination method. *J. Geophys. Res.*, **73**, 1299–1304.
32. van Bavel, C. H. M. (1966): Potential evaporation; the combination concept and its experimental verification. *Water Resour. Res.*, **2**, 445–467.
33. van Bavel, C. H. M., Lascano, R. J. & Stroosnijder, L. (1984): Test and analysis of a model of water use by sorghum. *Soil Sci.*, **137**, 443–456.
34. Willmott, C. J. (1982): Some comments on the evaluation of model performance. *Bull. Am. Meteorol. Soc.*, **63**, 1309–1313.