Studies on Evapotranspiration from Crops

(2) Separate Estimation of Transpiration and Evaporation from a Soybean Field without Water Shortage

Tetsuo SAKURATANI

(Div. Upland Farming, Kyushu Natl. Agric. Exp. Stn.,)
Yokoichi, Miyakonojo, 885 Japan.

Abstract

Stem heat balance method and Bowen ratio heat balance method were, respectively, used to determine transpiration (T) and evapotranspiration (ET) from a water-shortage free soybean field. Evaporation from the soil surface beneath the soybean canopy was indirectly estimated by subtracting T from ET . The diurnal change in the T/ET ratio was characterized by a parabolic curve with the minimum at noon, and higher values in the early morning and late afternoon, depending on the diurnal march of direct solar radiation intercepted by the canopy. Results showed that the evaporation from the soybean field at the early growing stage with sparse canopy was nearly equal to the evapotranspiration from the field at the later growing stage with dense canopy under a condition of enough soil moisture. The daily evaporation beneath the canopy decreased curvilinearly with the leaf area index (LAI). Combining the Makkink solar radiation model for estimating evapotranspiration and the transmission function of the canopy to global solar radiation yielded a simple model for estimating daily transpiration from the canopy. The transpiration estimated by this model increased curvilinearly with increment in the LAI . This relation was well approximated by a negative exponential function of leaf area index.

1. Introduction

As pointed out by Bierhuizen and Slatyer (1965) and Tanner (1981), photosynthesis and yield of crops are closely related to their transpiration rates. This principle has been successfully used to obtain models for estimating crop yield and biomass production (e.g. Hanks, 1974; Uchijima and Seino, 1985). They showed that yield and biomass production of plants increase proportionally to transpiration or evapotranspiration. In general, the determination of transpiration rates of crop canopies is somewhat difficult compared with that of evapotranspiration rate. In such models, therefore, it is often assumed that when the ground is completely covered with the plant canopy, the evaporation beneath the canopy is little and transpiration can be approximated by evapotranspiration with acceptable errors. However, we must check this assumption by experi-

ments of evapotranspiration and transpiration of crop fields.

Several semi-empirical models have been used for the separate estimation of transpiration and evaporation of upland fields (Ritchie and Burnett, 1971; Ritchie, 1972; Tanner and Jury, 1976; Kanemasu *et al.*, 1976) and rice fields (e.g. Uchijima, 1961). The evaporation or transpiration estimated by these models was usually compared not with directly measured evaporation or transpiration but with evapotranspiration obtained with a lysimeter. This is mainly because the direct measurement of transpiration rate of intact crops is not possible to date. To solve this difficulty, Sakuratani (1981) developed a heat balance method for measuring water flow rate in a thin stem of intact crops. This method has been successfully used to measure the transpiration rate of soybean and sugarcane under field conditions (Sato and Sakuratani, 1982; Sakuratani, 1982; Sakuratani and Abe, 1985).

In this paper, the stem heat balance method and

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Bowen ratio heat balance method were used to estimate separately transpiration of soybean canopy and evaporation beneath the canopy. The results so obtained were analyzed to make clear the dependence of transpiration and evaporation on the canopy denseness and solar radiation absorbed by the canopy.

2. Materials and Methods

2.1 Study site

The required microclimatic measurements were made during the respective growing periods of soybean in 1981 and 1983, at the experimental fields of National Institute of Agro-Environmental Sciences. In 1981, the soybean (cultivar Enrei) was planted on a field of 0.105 ha at the rate of 62,500 plants per hectare in 40-cm south-north rows on July 10. In 1983, the soybean was planted on a field of 0.64 ha at the rate of 149,000 plants per hectare in 60-cm south-north rows on July 10.

Thirty-two plants were sampled from the soybean fields every 5 or 6 days during its growing periods to determine the seasonal change in leaf area index (*LAI*); it was determined by multiplying the average leaf area per plant with the average number of plants per 1 m².

2.2 Estimate of evapotranspiration

The measurements of transpiration of the soybean canopy and evapotranspiration of the soybean fields were made on the fields using the stem heat balance method and Bowen ratio heat balance method during the period from July to September in 1981 and 1983.

The required measurements were made on a position in the field to take advantage of the longest unobstructed wind fetch available. Average evapotranspiration (*ET*) rate at every 30 minutes was calculated from the Bowen ratio heat balance equation;

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

where R_n is the net radiation flux density [$\text{W} \cdot \text{m}^{-2}$], G the soil heat flux density [$\text{W} \cdot \text{m}^{-2}$], β the Bowen ratio, and L the latent heat of evaporation [$\text{J} \cdot \text{kg}^{-1}$]. In 1981, temperatures of dry- and wet-bulbs were measured with aspirated copper-constantan thermometers at the heights of 10 and 80 cm above the canopy. In 1983, the measurements of these temperatures were made with the same thermome-

ters at the height of 15 and 115 cm above the canopy.

A Funk type polyethylene net radiometer set at 1 m above the canopy was used to measure the net radiation flux density on the field. Soil heat flux density was measured with three heat flux plates wired in series which were placed 1.0 cm below the soil surface at 20 cm intervals. The moisture tension in the soil was measured with mercury tentimeters placed vertically 10 cm below the soil surface.

Electric signals from the dry- and wet-bulb temperature-sensing elements, the net radiometer and the heat flux plates were fed to a multichannel automatic recorder in 1981. In 1983, each signal was inputted every 2 minutes with a computer-controlled data acquisition system.

2.3 Determination of transpiration

Transpiration rate (T) of the soybean was determined from

$$T = c \cdot n \cdot T_0, \quad (2)$$

where T_0 is the average rate of transpirational water loss per soybean plant [$\text{g} \cdot \text{s}^{-1}$] measured with the transpiration-measuring probe developed by Sakuratani (1981), n the average number of soybean plants per 1 m², and c a coefficient for converting total transpiration loss ($n \cdot T_0$) to water depth (mm) per 30 minutes ($c=1.8$).

Four and three sample plants were chosen near by the position for measurements of evapotranspiration to obtain the average value of T_0 in 1981 and 1983, respectively. The transpiration-measuring probe was set on the stem surface of each plant at 5–10 cm height above the ground surface, using the setting manner described in a previous paper (Sakuratani, 1981). The probes set on the stem surface were covered with heat insulator (sponge rubber) and aluminum foil reflector to minimize the thermal perturbation due to ambient air on the measurement. In 1981, the electric signals from the probe were fed to a low-noise amplifier and recorded on the multichannel recorder with strip chart speed of 25 mm·h⁻¹. In 1983, a computer-controlled data acquisition system was used to process the electric signals.

Because the long time setting of the probe on the stem suppresses inevitably the radial growth of the plant stem, the measurement of transpira-

tional water flow was usually limited to three days for the initial growth stage with the rapid radial growth of the stem and to a week for the later stage when *LAI* reached the maximum and the radial growth was gentle.

Immediately after the series of transpiration measurement finished, the probe was removed from the sample plant. The plant was cut above the ground surface to determine the leaf area and the cross-section of the stem on which the probe was set.

2.4 Estimate of evaporation

Evaporation (E) from the soybean field was estimated from

$$E = ET - T, \quad (3)$$

where ET is the evapotranspiration estimated from Eq. (1), and T the transpiration determined by the stem heat balance method. When the leaves were wetted by rain or dew, the evaporation estimated from Eq. (3) consists of evaporations of soil moisture and water on the leaves. In a case without rain drops or dew drops on the leaves, it shows the water loss from the soil surface beneath the canopy.

3. Results and Discussion

3.1 Applicability of stem heat balance method for determining transpiration rates

The average and standard error (SE) of transpiration rates determined by the stem heat balance method with the four sample plants were calculated to test the applicability of this method. The results are shown in Fig. 1 together with the diurnal march of net radiation and evapotranspiration of the soybean field. As shown in Fig. 1, the

Fig. 1. Diurnal course of net radiation (R_n), as equivalent rate of evaporation, evapotranspiration (ET) and transpiration (T) rates and percentage of standard error (PSE) on September 11, 1981.

Note: Each point (●) on the transpiration curve is the average of four measurements and the vertical bars show the magnitude of standard errors.

magnitude of SE of the average transpiration is between $\pm 2.6\%$ to $\pm 5.4\%$ of the average value of transpiration for 8:00–16:00 JST. The same analytical technique was also applied for the data obtained on August 27 and 30, 1981 and on August 8, 20 and 29, 1983. As summarized in Table 1, SE for the daytime period (8:00–16:00 JST) was between $\pm 2.6\%$ and $\pm 8.8\%$ of the

Table 1. Daily maximum (T_{max}) of T_{av} , range of diurnal change in PSE , and average value of the PSE .

Date	T_{max} (mm·30min ⁻¹)	Range (%)	Average (%)
Aug. 27, 1981	0.363	$\pm 3.8 \sim \pm 7.5$	± 5.5
Aug. 30, 1981	0.390	$\pm 2.8 \sim \pm 6.6$	± 4.5
Sept. 11, 1981	0.187	$\pm 2.6 \sim \pm 5.4$	± 3.6
Aug. 8, 1983	0.144	$\pm 5.1 \sim \pm 12.8$	± 8.8
Aug. 20, 1983	0.254	$\pm 0.3 \sim \pm 7.4$	± 2.6
Aug. 29, 1983	0.290	$\pm 1.3 \sim \pm 12.4$	± 5.7

Note: PSE refers to percentage of standard error of average transpiration rate (T_{av}) for four (in 1981) or three (in 1983) measurements to the T_{av} . The PSE was calculated for the period between 800 and 1600 JST.

average transpiration (T_{av}). From Fig. 1 and Table 1, we can conclude that the stem heat balance method with the three or four sample plants can be applied to determine the transpiration rate of soybean field with an acceptable error.

As shown in Fig. 1, the diurnal march of the transpiration is slightly different from that of the evapotranspiration, indicating that the sensitivity of transpiration rate on net radiation is less than that of evapotranspiration. At noon and in the late afternoon on September 11, 1981 the transpiration determined by the stem heat balance method was larger than the evapotranspiration estimated by the Bowen ratio heat balance method. This indicates that a part of water transported upwards in the stem is used for recovering water content in the plant decreased during the period with higher solar radiation. Therefore, when solar radiation changes irregularly with shorter interval, the error of the determination of transpiration by the stem heat balance method may become large. However, this method can be used for measuring transpiration as described in the previous report (Sakuratani, 1981), when the change in solar radiation is so slow as a quasi-steady state is maintained for the water balance in the plant.

3.2 Diurnal changes in transpiration, evaporation, and evapotranspiration

The data obtained on clear days during the growing period of soybean in 1981 were analyzed to study the diurnal changes in transpiration (T), evaporation (E) and evapotranspiration (ET). Fig. 2 shows the diurnal changes in T , E , ET , global solar radiation (R_s), net radiation (R_n), and air temperature (θ_a) on August 30 and September 17 with the wetted soil surface. Although there was no significant difference in net radiation and leaf area index between August 30 and September 17, the evapotranspiration rate on September 17 was 30 to 50 percent less than that on August 30, throughout the day. The difference in evapotranspiration is thought to be caused by the higher air temperature (θ_a in Fig. 2) on August 30, which probably resulted in the larger stomatal aperture.

Figure 2 also shows that the structure of evapotranspiration was significantly different between these two days. On August 30, the contribution of transpiration (T) to evapotranspiration (ET) was larger than that of evaporation (E), while on

Fig. 2. Diurnal course of global solar radiation (R_s), net radiation (R_n), air temperature (θ_a), transpiration (T), evaporation (E), and evapotranspiration (ET) on 30 August and 17 September, 1981.

September 17 the contribution of T to ET was nearly equal to that of E . On August 30, T increased rapidly with increasing net radiation (R_n), reached a peak at noon, and decreased with decreasing R_n in the afternoon. Although the evaporation on August 30 was in phase with the diurnal change in R_n , its absolute values were significantly lower than that of transpiration.

On the other hand, there was a clear difference in the diurnal march between transpiration (T) and evaporation (E) on September 17. The diurnal march of E was characterized by a curve with the two peaks in the early morning and around noon. The higher E in the early morning was considered to be due to the evaporation of dews on the leaves. The night of September 16/17 was so calm and clear, and net radiation was so low as a level of $-91 \text{ W} \cdot \text{m}^{-2}$ over the night that it was favorable for the dew fall. The higher E and lower T in the early morning on September 17 were probably because the radiation energy was mainly consumed to evaporate water not in leaves but on them. Such reduction of transpiration due to the use of radiation energy for evaporation of dew has been reported by several researchers (e.g. Slatyer, 1967).

In order to study the phenomenon mentioned

above in more detail, the diurnal course of the T/ET ratio was drawn in Fig. 3 using the data on three days when the soil surface was well moist. On August 30 and September 17 on which dew fall was expected during the nighttime, the T/ET ratio increased rapidly after the sunrise, reached the maximum, decreased gradually followed by the minimum at around noon, and increased again thereafter as shown in Fig. 3. On the other hand, on August 27 without dew fall, the diurnal march of the T/ET ratio was very simple and approximated by a curve with the minimum at noon and higher values in the early morning and late afternoon. This parabolic diurnal march of the T/ET ratio was expected to be related with the radiation amount intercepted by the canopy. The broken line in Fig. 3 shows the daytime change in the interception ratio (P) of direct solar radiation of the canopy calculated from the following equation (Ito and Udagawa, 1971) for August 30, 1981,

$$P = 1 - \exp(-G \cdot \text{cosec } h_o \cdot LAI), \quad (4)$$

where G is the mean effective leaf area function and h_o the solar elevation. It can be concluded from Fig. 3 that the daytime change in the T/ET ratio is correlated first with the interception of solar radiation and that this relation is disturbed in the early morning when dew or rain drops exist

Fig. 3. Diurnal course of the ratio of transpiration (T) to evapotranspiration (ET) on 27 and 30 August and 17 September, 1981.

Notes: 1) Solid lines are drawn by eye. 2) Broken line represents diurnal course of the direct sunlight interception ratio by the crop canopy, calculated from Eq. (4) using $G=0.40$ given empirically and $LAI=2.6$.

on the leaves.

3.3 Seasonal changes in transpiration, evaporation and evapotranspiration

Figure 4 shows the seasonal changes in daily values of transpiration, evaporation and evapotranspiration of the soybean field calculated on the basis of those half-hourly values. Those of T/ET ratio, LAI , solar radiation, soil moisture tension (pF), and precipitation are also shown in Fig. 4.

As shown in Figs. 4D and 4E, it was fair weather in early stage (except for the last decade of July) and in later stage at the maximum LAI , whereas it was cloudy with intermittent rain in development stage.

The values of evapotranspiration varied from 2 to $6 \text{ mm} \cdot \text{day}^{-1}$ during the growing seasons.

Fig. 4. Seasonal changes in transpiration (T), evaporation (E), evapotranspiration (ET), T/ET ratio, leaf area index (LAI), solar radiation, soil moisture tension (pF), and precipitation during the period from July 20 to September 7, 1983.

Although the daily transpiration changed largely depending on global solar radiation, it increased with LAI from the value lower than 1 mm at the early growing stage to the value higher than 3 to 5 mm at the maximum LAI stage. The daily transpiration (T) was normalized by daily evapotranspiration (ET) to make clear general characteristics of the seasonal changes in the transpiration. Fig. 4B shows the seasonal change in the T/ET ratio. Although the data points somewhat largely scattered, it is reasonable to conclude that the T/ET ratio increased proportionally with LAI (Fig. 4C). By taking the soil moisture condition and the presence of rain drops on the leaves into consideration, the data were divided into three groups (Fig. 4B); the group 1 (open circle) corresponds to the data obtained during the period with LAI lower than 3.0 and with soil moisture larger than pF 2.5 at 10 cm depth. The group 2 (square) is the data obtained during the rainy or overcast days when the percentage of possible sunshine was lower than 10%. The group 3 (closed circle) is characterized by the data obtained during days with wet soil surface and percentage of possible sunshine higher than 10%.

The data points in the group 1 were higher than the general trend curve, showing that the contribution of transpiration to evapotranspiration was higher than the other cases. This was mainly because the decrease of moisture content in the top soil layer limited more strongly the evaporation from soil surface than the transpiration. On the other hand, the data points for the group 2 were lower than the general trend curve. The downward deviation of the data points from the trend curve was ascribed to the fact that the main part of radiation energy was used for the evaporation of rain or dew drops on the leaves, reducing the transpiration. The data points of the group 3 were well distributed around the general trend line drawn to guide the reader's eye.

The above results show that the transpiration of soybean canopy can be determined by the leaf area index (LAI) and energy-limited evapotranspiration (where it means the evapotranspiration of crop fields under a condition of enough soil moisture (Tanner and Jury, 1976)).

3.4 Comparison of Priestley-Taylor model and Makkink radiation model for estimating evapotranspiration

Daily evapotranspiration (ETP_P) estimated by Priestley-Taylor (1972) model (Eq. (5)) was compared with that (ETP_R) estimated by Makkink (1957) radiation model (Eq. (6)).

$$ETP_P = \alpha \frac{\Delta}{\Delta + \gamma} \cdot \frac{R_n}{L}, \quad (5)$$

$$ETP_R = a \frac{\Delta}{\Delta + \gamma} \cdot \frac{R_s}{L}, \quad (6)$$

where R_s the daily global solar radiation [$\text{MJ} \cdot \text{m}^{-2}$], Δ the slope of saturated vapor pressure vs. temperature curve at mean air temperature [$\text{mb} \cdot ^\circ\text{C}^{-1}$], γ the psychrometer constant [$\text{mb} \cdot ^\circ\text{C}^{-1}$], α and a the proportionality constants. Because the daily value of evapotranspiration is considered here, Eqs. (5) and (6) ignore the soil heat flux as a first approximation.

Although Priestley and Taylor (1972) have considered α as a constant ($\alpha = 1.26$), it has been reported by many researchers (e.g. Pruitt and Doorenbos, 1977; Nakayama and Nakamura, 1982; Sakuratani and Horie, 1985) that the value of α changes in regions and during season. Furthermore, Sakuratani and Horie (1985) found in a rice field that the seasonal change in the value of a in Eq. (6) was substantially less than that of α in Eq. (5).

Figure 5 also shows that the values of α and a calculated from Eqs. (5) and (6) changed with season. These two constants were large during the period from August 15 to August 24 with intermittent rainy days and small during the period from August 6 to August 13 with the dry soil surface. In the periods from July 24 to July 31

Fig. 5. Seasonal changes in daily values of α and a in 1983.

and from August 25 to September 7, these two constants showed no significant change in the magnitude. Namely, the value of α was over a range between 1.05 for the period from July 24 to July 31, and 1.32 for the period from August 25 to September 7. The change in the value of constant a was little in comparison with that of α and it was over a range 0.72 to 0.78 with the average of 0.75. Therefore, the Makkink solar radiation model was used for estimating energy-limited evapotranspiration (ETP) of soybean fields by assuming $a=0.75$.

3.5 A simple method for estimating transpiration

When evapotranspiration and evaporation are estimated from appropriate methods, the canopy transpiration can be easily estimated from subtracting evaporation from evapotranspiration. Tanner and Jury (1976) calculated the energy-limited evapotranspiration (ETP) and evaporation (EP) using the Priestley-Taylor model and a somewhat modified model, and estimated the canopy transpiration.

The author tried the estimation of ETP and EP , and consequently T using the Makkink solar radiation model. The global solar radiation model for estimating EP was assumed to be principally equal to Eq. (6),

$$EP = a_0 \frac{A}{A+r} \cdot \frac{R_{s0}}{L}, \quad (7)$$

where R_{s0} the daily solar radiation flux density [$\text{MJ} \cdot \text{m}^{-2}$] on the ground surface under the crop canopy, and a_0 a proportionality constant. The following empirical relation was used to estimate R_{s0} ,

$$R_{s0} = R_s \cdot \exp(-k \cdot LAI), \quad (8)$$

where k is the extinction coefficient for global solar radiation. By combining Eqs. (6), (7) and (8), and assuming that a_0 is equal to a , for the simplicity, we obtained finally

$$T = a \frac{A}{L(A+r)} \cdot [1 - \exp(-k \cdot LAI)] \cdot R_s, \quad (9)$$

By putting $a=0.75$ described above and $k=0.9$ for horizontal leaved canopies (Horie, 1981) into Eq. (9), the energy-limited transpiration (T_{cal}) of soybean canopy was calculated. The values of T_{cal} were compared with those of the transpiration (T_{meas}) measured with the stem heat balance

Fig. 6. Comparison of the transpiration (T) calculated from Eq. (9) with the observed T in 1983.

method to verify the applicability of Eq. (9). Figure 6 shows that there was a good agreement between them, where the following regression equation was obtained with the correlation coefficient of 0.967;

$$T_{cal} = 0.961 T_{meas}. \quad (10)$$

The above results show that the derived simple method (Eq. 9) can be used to estimate canopy transpiration of soybean fields without water shortage.

As Wilson and Rouse (1972) have reported, the value of $A/(A+r)$ is not very sensitive to change in temperature over a range above 17°C . In the present study, daily average of air temperature was between 21 and 26°C , corresponding to the change in the value of $A/(A+r)$ from 0.69 to 0.74 . Therefore, we can conclude that the transpiration from the soybean canopy is first affected by the absorption of global solar energy by the canopy that is approximated by $[1 - \exp(-k \cdot LAI)] \cdot R_s$. The existence of a linear relation with so higher correlation coefficient as 0.961 between absorbed solar radiation and measured transpiration (T_{meas}) gives a strong support to the above conclusion. A similar conclusion was also obtained by Uchijima (1961) between net radiation absorbed by rice canopy and transpiration of rice canopy. Because net radiation has a close correlation to global solar radiation, his result agreed principally with the present results.

Equation (9) shows that the radiation-limited transpiration increases to an asymptotic value with increasing LAI . From Eqs. (6) and (9), we can obtain the following relation;

$$\frac{T}{ETP_R} = [1 - \exp(-k \cdot LAI)] \quad (11)$$

Equation (11) was basically the same as the relationship between LAI and T/ET ratio obtained by Uchijima (1961) for a rice field.

Figure 7 shows the exponential dependence of T/ETP_R on LAI obtained by analyzing experimental data of the soybean field. The solid line on this figure is determined from Eq. (11) using $k=0.9$. Although the data points scattered somewhat largely, these were well distributed around the semi-empirical curve, showing that Eq. (11) can be used to make clear the structure of evapotranspiration of plant canopy.

Fig. 7. Dependence of the ratio of transpiration (T) to energy-limited evapotranspiration (ETP_R) estimated from the solar radiation model on leaf area index in 1983.

As shown in Fig. 7, although the T/ETP_R ratio increased first proportionally with LAI when LAI is lower than 1.5, the increasing rate of the ratio decreased gradually with increasing LAI , and approached to the asymptotic level. Richie and Burnett (1971) defined the threshold LAI as a value at which the T/ETP ratio reaches 90% and becomes insensible to the increase in LAI . For the soybean field from Fig. 7, threshold LAI was estimated at a value of 2.6 which agrees well with the threshold LAI (2.7) for cotton and sorghum fields obtained by Richie and Burnett (1971).

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References

- Bierhuizen, J. F. and Slatyer, R. O., 1965: Effect of atmospheric concentration of water vapor and CO_2 in determining transpiration-photosynthesis relationships of cotton leaves. *Agric. Meteorol.*, **2**, 295–270.
- Hanks, R. J., 1974: Model for predicting plant yield as influenced by water use. *Agron. J.*, **66**, 660–665.
- Horie, T., 1981: System ecological studies on crop-weather relationships in photosynthesis, transpiration and growth. *Bull. Natl. Inst. Agric. Sci.*, **A28**, 1–181.*
- Ito, A. and Udagawa, T., 1971: Phytometrical studies of crop canopies (1)—Geometrical structure of soybean canopy and sun light penetration—. *J. Agr. Met.*, **26**, 187–195.*
- Kanemasu, E. T., Stone, L. R. and Powers, W. L., 1976: Evapotranspiration model tested for soybean and sorghum. *Agron. J.*, **68**, 569–572.
- Makkink, G. F., 1957: Ekzamenno de formulo de Penman. *Neth. J. Agric. Sci.*, **5**, 290–305.
- Nakayama, K. and Nakamura, A., 1982: Estimating potential evapotranspiration by the Priestley-Taylor model. *J. Agr. Met.*, **37**, 297–302.*
- Priestley, C. H. B. and Taylor, R. J., 1972: On the assessment of surface heat flux and evaporation using large-scale parameters. *Mon. Weather Rev.*, **100**, 81–92.
- Pruitt, W. O. and Doorenbos, J., 1977: Empirical calibration, a requisite for evapotranspiration formulae based on daily or longer mean climatic data. (quoted in: Burman, R. D. et al., Techniques for estimating irrigation water requirements. In: *Advances in Irrigation* Vol. 2, ed. D. Hillel, Academic Press, New York, 429pp).
- Ritchie, J. T., 1972: Model for predicting evaporation from a row crop with incomplete cover. *Water Resources Res.*, **8**, 1204–1212.
- Ritchie, J. T. and Burnett, E., 1971: Dryland evaporative flux in a subhumid climate: II. Plant influences. *Agron. J.*, **63**, 56–63.
- Sakuratani, T., 1981: A heat balance method for measuring water flux in the stem of intact plants. *J. Agr. Met.*, **37**, 9–17.
- Sakuratani, T., 1982: Two thermic method for measuring water flux in the stem of intact plants and their applications. *Bull. Nat. Inst. Agr. Sci.*, **A29**, 47–121.*

- Sakuratani, T. and Abe, J., 1985: A heat balance method for measuring water flow rate in stems of intact plants and its application to sugarcane plants. *JARQ*, **19**, 92–97.
- Sakuratani, T. and Horie, T., 1985: Studies on evapotranspiration from crops. (1) On seasonal changes, varietal differences and the simplified methods of estimate in evapotranspiration of paddy rice. *J. Agr. Met.*, **41**, 45–55.*
- Sato, K. and Sakuratani, T., 1982: Water consumption at different levels of soybean canopies of different plant spacings in the field estimated from the water fluxes in the stem. *Jpn. J. Crop Sci.*, **51**, 75–81.*
- Slatyer, R. O., 1967: *Plant-Water Relations*. Academic Press, New York, 366 pp.
- Tanner, C. B., 1981: Transpiration efficiency of potato, *Agron. J.*, **73**, 59–64.
- Tanner, C. B. and Jury, W. A., 1976: Estimating evaporation and transpiration from a row crop during incomplete cover. *Agron. J.*, **68**, 239–243.
- Uchijima, Z., 1961: On characteristics of heat balance of water layer under paddy plant cover. *Bull. Natl. Inst. Agr. Sci.*, **A8**, 243–265.
- Uchijima, Z. and Seino, H., 1985: Agroclimatic evaluation of net primary productivity of natural vegetatives. (1) Chikugo model for evaluating net primary productivity. *J. Agr. Met.*, **40**, 343–352.
- Wilson, R. G. and Rouse, W. R., 1972: Moisture and temperature limits of equilibrium evapotranspiration model. *J. Appl. Met.*, **11**, 436–442.

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作物の蒸発散に関する研究 (2) 大豆畑の蒸散量と蒸発量の分離評価

桜谷 哲夫

(九州農業試験場畑作部)

要 約

大豆畑からの蒸発散量 (ET) を蒸散量 (T) と蒸発量 (E) に分離して評価するために、 ET をボーエン比熱収支法により、 T を茎熱収支法により求めた。 E は ET と T との差で与えられた。測定は1981年と1983年にそれぞれ0.105 h 及び0.64 haの畑(品種エンレイ)で行った。得られた結果は次のように要約される。

1) 圃場蒸散量は茎熱収支法から求められる測定個体の平均蒸散量 (T_0) から(2)式を用いて外挿されたが、 T_0 の個体による差が比較的小さいため、4本の測定個体から個々に推定した T には大差がなかった (Fig. 1)。 T と ET との経時変化の間には若干のタイムラグが認められたが、準定常状態の下での値または日平均値を用いることによってこの影響は消去できるものと考えた。

2) 早朝には T が抑制された日があったが、これは露によるものと考えられた。このような日には E は双頂型の日変化を示した (Fig. 2)。 T/ET 比は一般に正午を最小とする日変化曲線で表わされ、この日変化は植被層

の見掛けの日射吸収率の日変化とはほぼ平行関係にあった (Fig. 3)。

3) 生育初期の前半は土壌面が湿潤状態であったため ET は生育最盛期のそれに匹敵し、 E は生育初期から最盛期にかけて減少する傾向にあった。 T/ET 比は土壌水分と天候の影響を大きく受け土壌面の乾燥時には大きな値を、曇雨天日には小さい値を示す傾向にあった (Fig. 4)。

4) 湿面からの蒸発散量推定のための日射法の係数 a の季節による変動は、Priestley-Taylor法の係数 α より小さく、大豆畑における日射法の有効性が確かめられた (Fig. 5)。

5) 日射法が植被下の湿潤土壌面からの蒸発量推定にも利用できるものとして日蒸散量を推定するための簡易な半経験式を導いた。この式から、 LAI に対する T の増加はおおむね $LAI=26$ で鈍化すること (Fig. 7)、 T は見掛けの吸収日射量に比例することが分かった。