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論文
Original Paper

Evaluation of energy-balance-based evapotranspiration in a grass field

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Abstract : The proper estimates of evapotranspiration (ET) are critical for better animal manure and/or water management practices in farmlands. Micrometeorological methods, *e.g.*, the Bowen ratio method and the eddy covariance method, to estimate ET have been popularly used. Those methods, however, require specially-designed instruments or the multiple numbers of instruments. Estimates of ET based on the energy balance at the canopy surface, on the other hand, need only routine weather data that were easily available. Evapotranspiration estimated by the energy balance method along with routinely-obtained weather data was evaluated by comparing with estimates of ET by the Bowen ratio method. Weather data, *i.e.* shortwave irradiance, R_s (W m^{-2}), air temperature, T_a (K), relative humidity, and wind speed, required for the energy balance method were measured in a reed canarygrass field located near Morioka in north-eastern Japan. A Bowen ratio system was installed alongside in the same grass field. An energy balance on a grass canopy is expressed as a function of canopy surface temperature, T_s (K). Using the Newton-Raphson method, the energy balance equation was numerically solved for T_s, to obtain an evapotranspiration rate, E (kg m^{-2} s^{-1}). Values of net irradiance, R_n (W m^{-2}) and latent heat flux, LE (W m^{-2}), were overly estimated with the energy balance method when $R_n > 500$W m^{-2}. For $R_n < 500$W m^{-2}, however, R_n, LE, and sensible heat flux, H (W m^{-2}), estimated with the energy balance method agreed well with those estimated with the Bowen ratio method. Daily ETs between July 1 and 28, 2003 were calculated by accumulating E between sunrise and sunset. The daily ET values obtained by the two methods agreed very well with the correlation coefficient, $r = 0.96$ ($P < 0.001$). The energy balance method to estimate daily ET could be promising.

Keywords : Evapotranspiration, Bowen ratio method, Energy balance method, Atmospheric emissivity, Crop height

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1. Introduction

Surface- and/or ground-water pollution with animal wastes is prohibited by the law in Japan. The proper management of dairy cattle manure for applying to an agricultural grass field, which is popular in the areas with large livestock industry, is very critical for the livestock industry. Prior to the application of dairy cattle manure, soil water content in the field must be known to minimize surface runoff and/or deep percolation. The proper estimation of soil water content depends on how well evapotranspiration (ET) is predicted or measured. Measuring ET is usually made by means of lysimeter, soil water balance, energy balance, and eddy covariance methods. Some methods require specifically-designed equipments whereas others just use routine weather data. From the practical view of farmers, the latter methods would be appreciated.

Penman (1948) would be the first to develop a model to estimate ET using meteorological data. Penman's model is modified into various models, and so-called the Penman-Monteith model has been very popular and extensively evaluated by many researchers (Kustas et al., 1996; Howell and Evett, 2004; Gong et al., 2006). In Penman's procedure, evaporating surface temperature is not required because he assumed a linear relationship between saturated vapor density and air temperature over a narrow range of 10K (Monteith and Unsworth, 2008). With the improvement of digital computing power, however, numerical iteration procedures, which are able to solve a full energy balance equation on an evaporating surface, are readily available to estimate ET with few assumptions (Van Bavel and Lascano, 1987). Van Bavel and Lascano (1987) model predicts ET and the profile of water content and temperature in soil. Since their model deals with water and heat transport in soil, data for root distribution are required.

We tested a sort of a submodel, estimating ET using weather data, of Van Bavel and Lascano (1987) or of an extended model of Van Bavel and Hillel (1976). The model that we tested used numerical iteration, with no soil and root parameters nor any assumptions such as Penman (1948) made, to estimate canopy temperature and then eventually ET. Testing this kind of submodel will provide with the feasibility of a simple-yet-fully-theoretical ET model. Evaluation of the model proposed was made by comparing ET estimated with that measured with the Bowen ratio method.

2. Materials and Methods

2. 1 An energy balance at a canopy surface

An energy balance equation, $f(T_s)$, at a bare soil surface is expressed as a function of surface temperature, T_s, (Van Bavel and Hillel, 1976) as：

$$f(T_s) = R_n(T_s) + LE(T_s) + H(T_s) + G(T_s) = 0 \quad [1]$$

where $R_n(T_s)$ is the net irradiance (W m^{-2}), $LE(T_s)$ is the latent heat flux (W m^{-2}), $H(T_s)$ is the sensible heat flux (W m^{-2}), and $G(T_s)$ is the soil heat flux (W m^{-2}) that could be measured with a heat flux plate. Fluxes away from the surface are expressed as negative, and are those toward the surface as positive. We assumed that Eq. [1] was also true at the canopy surface in a grass field where the soil surface was fully covered with reed canarygrass. In this case, T_s in Eq. [1] indicates the canopy surface temperature (K).

Net irradiance, $R_n(T_s)$, is expressed as the sum of incoming and outgoing shortwave and longwave irradiances as a function of surface temperature, T_s, (Noborio et al., 1996a) as：

$$R_n(T_s) = (1-\alpha)\, R_s + \varepsilon_s \varepsilon_a \sigma T_a^4 - \varepsilon_s \sigma T_s^4 \quad [2]$$

where α is the albedo of the canopy surface, which was measured with pyronometers in our case, R_s is the incoming shortwave irradiance (W m^{-2}), ε_s and ε_a are the emissivities of the canopy surface and the atmosphere, respectively, T_a is air temperatures (K), and σ is the Stephan-Boltzmann constant (= 5.67 x 10^{-8} W m^{-2} K^{-4}). The canopy surface emissivity, ε_s, was chosen as 0.97 according to Campbell (1977). The atmospheric emissivity, ε_a, is calculated (Campbell, 1985) as：

$$\varepsilon_a = (1-0.84C_L)(850.0\,\rho_a^{1/7}) + 0.84C_L \quad [3]$$

where ρ_a is the water vapor density (kg m^{-3}) of air. The fraction of cloud cover, C_L, is estimated (Campbell, 1985) as：

$$C_L = 2.33 - 3.33T_t \quad [4]$$

where T_t is the total atmospheric transmission coefficient for solar radiation defined as a ratio of potential to measured shortwave irradiance, R_s. The potential shortwave irradiance is a function of the solar constant (≈1367 W m^{-2}) and the locations of the sun and an observer. See Campbell (1985) for a detailed calculation procedure for the potential shortwave irradiance.

The latent heat flux, $LE(T_s)$, is expressed as a function of T_s (Van Bavel and Hilell, 1976) as：

$$LE(T_s) = L\frac{\rho_a(T_a) - \rho_s(T_s)}{r_V} \quad [5]$$

where L is the latent heat (J kg^{-1}) of vaporization of water, E is the evapotranspiration rate (kg m^{-2} s^{-1}), $\rho_s(T_s)$ is the water vapor density (kg m^{-3}) at the canopy surface, and r_V is the aerodynamic resistance (s m^{-1}) for water vapor transport. The latent heat, L (J kg^{-1}), of vaporization of water is derived from the data of Monteith and Unworth (2008) as：

$$L = 2.201 \times 10^6 - 2369.2\,(T - 273.15) \quad [6]$$

where T is temperature (K). Water vapor density at the evaporating surface, $\rho_s(T_s)$, was assumed to be saturation at the canopy temperature, T_s, because the humidity of stomatal cavities is always near unity (Campbell, 1985). Saturation water vapor density, ρ^o (kg m^{-3}), is estimated (Campbell, 1985) as：

$$\rho^o = \frac{\exp\left(31.3716 - \dfrac{6014.79}{T} - 0.00792495T\right)}{T}\, 0.001. \quad [7]$$

Water vapor density of air, $\rho_a(T_a)$, is then calculated as the product of ρ^o and the relative humidity, RH, of air.

The sensible heat flux, $H(T_s)$, is expressed as a function of T_s (Van Bavel and Hilell, 1976) as：

$$H(T_s) = C_{pa}\frac{T_a - T_s}{r_H} \quad [8]$$

where C_{pa} is the volumetric heat capacity of air (≈1200 J m^{-3} K^{-1}), T_a is air temperatures (K), and r_H is the aerodynamic resistance (s m^{-1}) for heat transport. The aerodynamic resistances, r_V and r_H, are assumed to be equal at the canopy surface and are described (Campbell, 1977) as：

$$r_H = r_v = \frac{\ln[(z + z_H - d)/z_H]\,\ln[(z + z_H - d)/z_M]}{k^2\overline{u}} \quad [9]$$

where k is the Karman's constant (≈0.4), z is the height (m) above the ground where the temperature and wind speed are measured, d is the zero plane displacement (m) for the surface, $\bar{u}$ is the mean wind speed (m s^{-1}) at the height z (m), and z_H and z_M are the roughness lengths (m) for heat and momentum, respectively. For typical plant surfaces, the following empirical relationships with the plant height, h (m), are used (Campbell, 1985) as：

$$d = 0.77h \quad [10]$$

$$z_M = 0.13h \quad [11]$$

$$z_H = 0.2z_M. \quad [12]$$

Since the energy balance equation, Eq. [1], is expressed as a function of the canopy surface temperature, T_s, Eqs. [1], [2], [5], and [8] are numerically solved for T_s using the Newton–Raphson method (Press et al., 2002). Assuming that the initial value of T_s was equal to T_a, the Newton–Raphson method solved Eq. [1] with respect to T_s as:

$$T_s^{n+1} = T_s^n - \frac{f(T_s^n)}{f'(T_s^n)} \quad [13]$$

where the superscripts n and n+1 indicate the number of iterations, $f'(T_s)$ was the first derivative of $f(T_s)$ with respect to T_s, that might be numerically derived as：

$$f'(T_s) = \frac{f(T_s+\Delta T_s) - f(T_s-\Delta T_s)}{2\Delta T_s} \quad [14]$$

where ΔT_s was the small increment of T_s, e.g., $\Delta T_s = 1.0 \times 10^{-6}$.

After several iterations of Eq. [13], T_s satisfying Eq. [1] was found. The evapotranspiration rate, E (kg m^{-2} s^{-1}), was estimated using Eq. [5] by applying the iteratively–found T_s value. Dividing E by the density of water, $\rho_w = 1000$ kg/m^3, and summing up E/ρ_w between sunrise and sunset estimated the daily evapotranspiration, ET (mm d^{-1}) .

2. 2 Bowen ratio method

The Bowen ratio method has been used to measure evapotranspiration in the field as a standard method. Taking the ratio, $\beta = H/LE$, called the Bowen ratio, and rearranging Eq. [1] with respect to LE provides (Campbell, 1977)：

$$LE = -\frac{R_n + G}{1 + \beta} \quad . \quad [15]$$

From Eqs. [5] and [8], the Bowen ratio, β, is expressed (Campbell, 1977) as

$$\beta = \frac{H}{LE} = \frac{C_{pa}(T_1 - T_2)}{L(\rho_1 - \rho_2)} \frac{r_V}{r_H} \quad [16]$$

where the subscripts 1 and 2 indicate values of the variables at heights z_1 and z_2, and it was assumed to be $r_V = r_H$ as mentioned in Eq. [9].

2. 3 Measurement

Experiments were conducted in July 2003 in northern Honshu, Japan (39°48' N, 141°05' E). An experimental plot raising reed canarygrass (*Phalaris arundinacea L.*) was managed by a farmer with routine work in a usual manner. The area of the experimental plot, sloped with about 5.5 degrees from the northwest to the southeast, was approximately two hectare. The taxonomical class of soil was Andisol with 80 % of sand, 12 % of silt, and 8 % of clay.

Weather data, *i.e.* incoming shortwave irradiance, R_s (W m^{-2}), reflected shortwave irradiance, R_r (W m^{-2}), air temperature, T_a (K), relative humidity, RH, and wind speed, u (m s^{-1}), were measured at height $z = 2$ m. Soil heat flux, G (W m^{-2}), was measured using three heat flux plates (MF–81, EKO Instruments Co.,Ltd., Tokyo) at 0.05m deep from the soil surface. Incoming and reflected shortwave irradiances, with which albedo α was determined, were measured with pyronometers (MS–601, EKO Instruments Co.,Ltd., Tokyo), an air temperature and humidity sensor (CS500, Campbell Scientific Inc., Logan, UT), were used. Wind speed and wind direction were measured with a three–cup–anemometer and a wind–vane (03001, Campbell Scientific Inc., Logan, UT). Precipitation was measured with a tipping–bucket rain gauge (K. Hattori & Co., Ltd., Tokyo). Data were acquired every second, and mean values were stored using a datalogger (CR23X, Campbell Scientific Inc., Logan, UT) every 15 min.

A Bowen ratio system (Campbell Scientific Inc., Logan, UT) was installed alongside. Air temperature and water vapor density of air were measured at heights $z_1 = 2$ m and $z_2 = 1$ m. Air temperature was measured with fine fire type–E thermocouple junctions, and water vapor density was measured with a cooled mirror hygrometer (Dew–10, General Eastern Corp., Watertown, MA). Fetch was at least 40 m radius, which satisfied the minimal fetch requirement, fetch > $20z_1$ (Heilman et al., 1989), surrounding the Bowen ratio system. A net radiometer (Q7.1, Campbell Scientific Inc., Logan, UT), 1.5 m high above the ground, and two heat flux plates (HFT3, Campbell Scientific Inc., Logan, UT), 0.08 m deep from the soil surface, were also installed. Soil temperatures at 0.02 m and 0.06 m below the soil surface were measured with type–T thermocouple junctions. Soil water content was also measured with a CS615 moisture sensor (Campbell Scientific Inc., Logan, UT) at 0.025 m below the soil surface. Data for the Bowen ratio system were measured every second, and mean values were stored every 20 min. using a datalogger (CR23X, Campbell Scientific Inc., Logan, UT).

3. Results and Discussion

3. 1 Energy components

The maximal T_s value estimated with Eq. [1] was found at around 11 : 00 whereas the maximal T_a value was found at around 14 : 00 (Fig. 1). The values of R_n reached the maximal at around noon because the magnitude of shortwave irradiance was largely affected by the sun's location (Fig. 3A). Noborio et al. (1996b) reported that the surface temperature estimated by the energy balance method agreed well with that measured at the bare soil surface.

Figure 2 shows that temporal changes in energy flux densities obtained using the Bowen ratio system for a clear day on July 27, 2003. The signs of all the energy flux densities in Fig. 2 are expressed as positive for convenience. The values of R_n and G were measured using the instruments whereas the values of LE and H were estimated using Eqs. [15] and [16], respectively. Approximate 73 % of incoming total energy, *i.e.* R_n, was consumed for evapotranspiration (ET), *i.e.* LE, whereas approximate 18 % of R_n was consumed for H.

Mayocci and Bristow (1995) proposed that soil heat flux, G, be corrected for the heat storage of soil above a heat flux plate. We, however, did not correct G, but used raw G to calculate LE because just < 3 % as little as R_n accounted for G during daytime when evapotranspiration was obvious.

Energy flux densities estimated with the energy balance method were compared with those measured with the Bowen ratio method (Fig. 3). In Eqs. [9] and [10], crop height, h, was assumed to be 0.1 m all the time. The effects of crop height on ET will be discussed in the following section. Equation [2] of the energy balance method overly estimated 20 % as much as R_n measured with the net radiometer during midday when R_n > 500W m^{-2} (Fig. 3A). Overestimates of R_n may be attributed to the overestimate of the atmospheric emissivity, ε_a, calculated with Eq. [3]. Unlike Fig. 2A, Noborio et al. (1996b) reported that R_n estimated in a similar manner using Eq. [3] performed well for the bare soil surface in Texas, U.S.A. When R_n < 500W m^{-2}, however, estimates of R_n with Eq. [2] agreed well with R_n measured. Overestimates of R_n resulted in overestimates of LE by Eq. [5] of the energy balance method (Fig. 3B). Likewise did R_n < 500W m^{-2}, LE estimated with Eq. [5] agreed well with that measured with the Bowen ratio method with Eq. [15] when LE < 300 – 400W m^{-2}. The resultant, H, agreed well with both methods (Fig. 3C) although their phase started to shift by following the phase shift in G (Fig. 3D). In Fig. 3D, the amplitude of Gs agreed well ; however, their phases shifted. The phase shift might be resulted from differences in the installation depths of two methods, the energy balance method in 0.05 m deep and the Bowen ratio method in 0.08 m deep. The heat flux plates at a shallower depth started to change earlier than those at a deeper depth. Because the contribution of G to the energy balance was small enough comparing with other components in Eq. [1], we

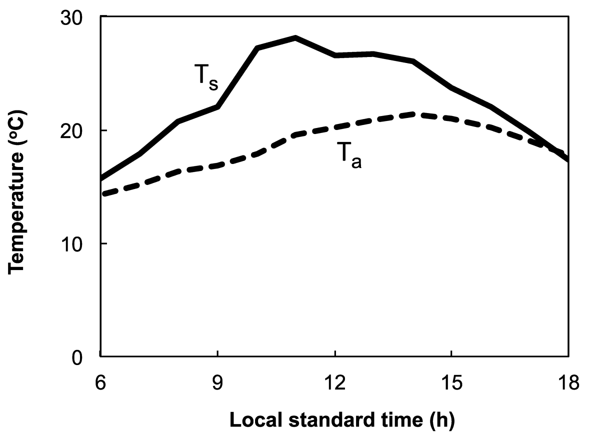

Fig. 1 Temporal changes in air temperature, T_a, measured at the weather station in the field and canopy temperature, T_s, estimated using Eq. [1] by the energy balance method. The crop height was assumed to be a constant as h = 0.1 m, and data used for calculation were obtained on July 27, 2003.

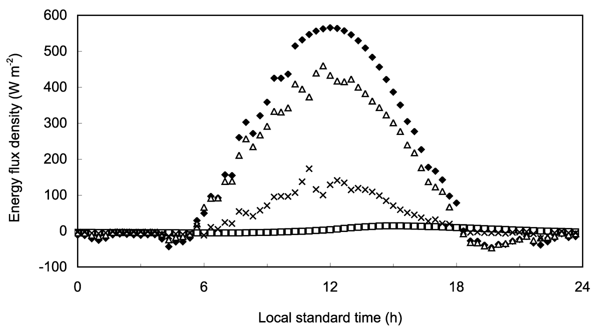

Fig. 2 Energy flux densities measured on July 27, 2003 with the Bowen ratio system. Symbols of solid diamonds, open triangles, crosses, and open squares indicate R_n, $-LE$, $-H$, and $-G$, respectively.

thought that the phase shift was negligible.

3. 2 Evapotranspiration

Daily ETs between July 1 and 28, 2003 were calculated by accumulating E between sunrise and sunset. Figure 4 showed that daily ET values with a range between $0.2\,\mathrm{mm\,d^{-1}}$ and $5\,\mathrm{mm\,d^{-1}}$ using a constant h value (= 0.1 m) agreed very well with those by the Bowen ratio method with correlation coefficient $r = 0.96$ (probability $P < 0.001$), and they were close to the 1 : 1 line. In reality, however, crop height, h, increased with

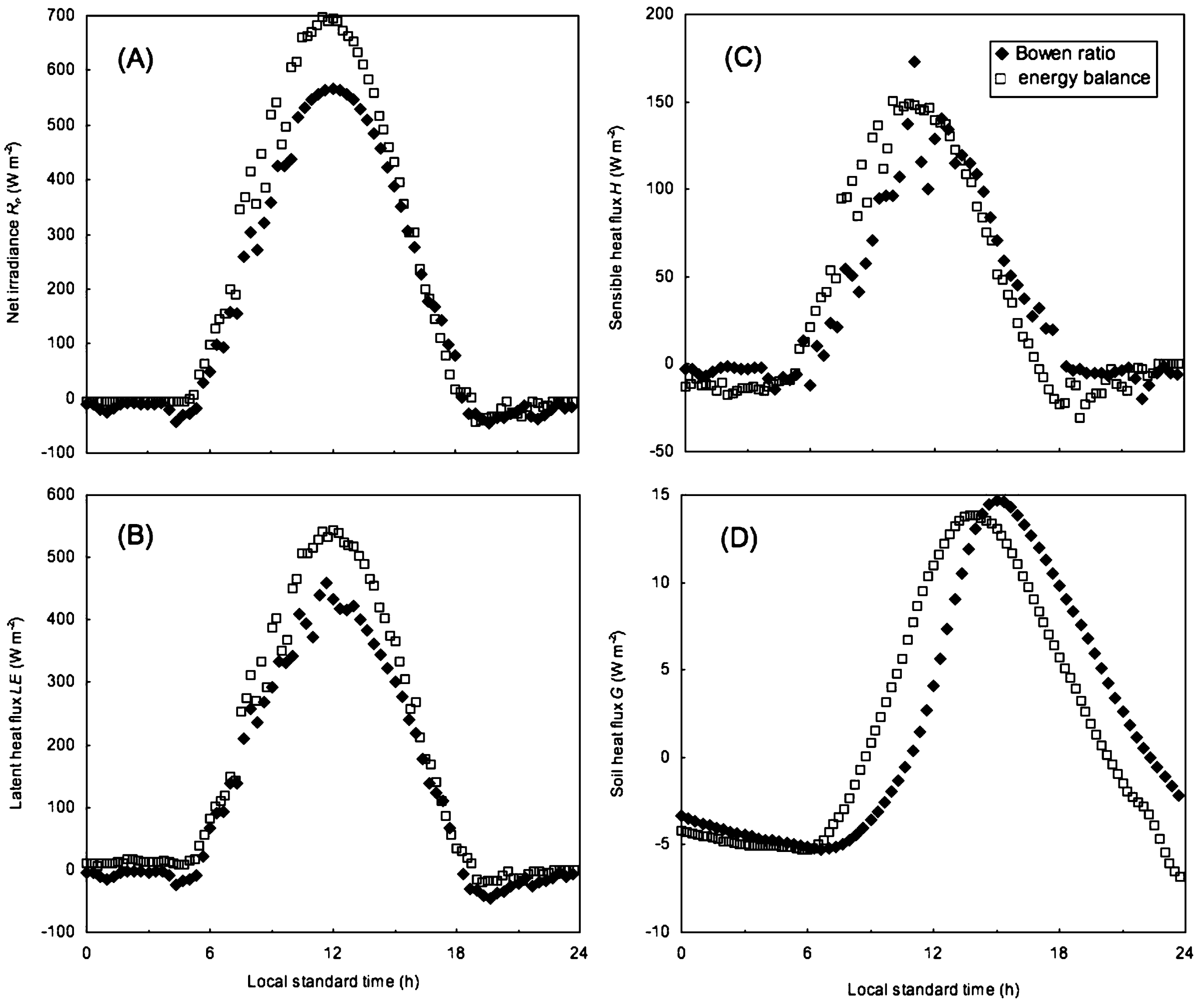

Fig. 3 Comparing energy flux densities, (A) R_n, (B) $-LE$, (C) $-H$, and (D) $-G$, between the energy balance method and the Bowen ratio method. The densities were measured and estimated on July 27, 2003.

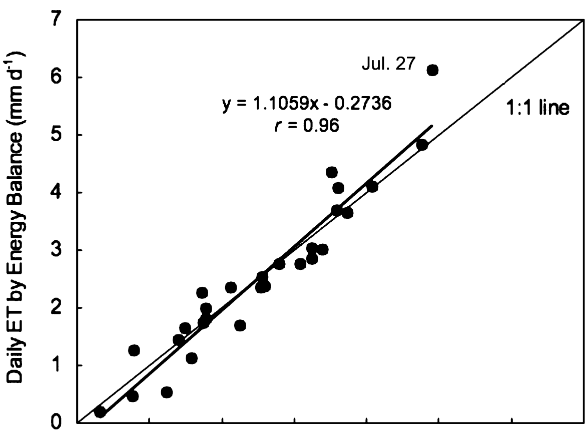

Fig. 4 Comparing daily evapotranspiration (ET) between the energy balance method and the Bowen ratio method between July 1 and July 28, 2003.

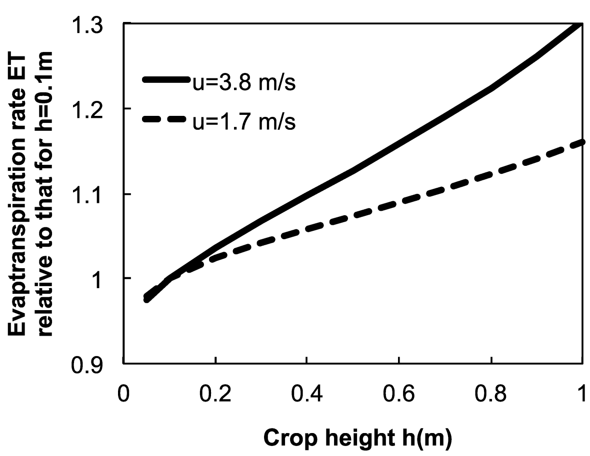

Fig. 5 The dependence of evapotranspiration (ET) on the crop height (h) varied with wind speed. Wind speed is described as u. Data used for calculation were obtained at 11:45 local standard time on July 27, 2003.

time according to accumulating mean daily temperature.

When varying h from 0.05 m to 0.9 m with time was used for Eqs. [9], [10], and [11], daily ETs were a little bit more overly estimated than those using $h = 0.1$ m (Fig. 5). Increases in h resulted in smaller r_V and eventually larger LE. The ET relative to that calculated with $h = 0.1$m at approximately noontime in the clear day increased by 30 % as increases in the values of h when wind speed, u (m), was larger (Fig. 5). An extreme case like this made an off placed datum indicated with Jul. 27 in Fig. 4. Unlike the case of Jul. 27, the ETs of other days were properly estimated using Eq. [1] as shown in Fig. 4. For the other days, overestimates of R_n due to overestimates of ε_a with Eq. [3] compensated underestimates of ET due to underestimates of h, and eventually daily ETs estimated with Eq. [1] agreed well with those measured by the Bowen ratio method.

4. Conclusion

The energy balance method was applied to estimate evapotranspiration (ET) using routine weather data. Although it overly estimated R_n and LE only when $R_n > 500$W m^{-2}, estimates of daily ET ranging between 0.2 mm d^{-1} and 5 mm d^{-1} agreed well with ET measured with the Bowen ration method. To properly estimate a full range of ET rates, atmospheric emissivity, ε_a, expressed with Eq. [3] should be calibrated for Japanese environmental conditions or the use of a net radiometer to directly measure R_n is recommended. Evapotranspiration in the field could be easily estimated by the energy balance method using routine weather data, i.e. shortwave irradiance, air temperature, relative humidity of air, wind speed, and/or soil heat flux, from a field server such as reported by Manzano et al. (2011).

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References

Campbell, G.S., 1977 : *An introduction to environmental biophysics*. Springer–Verlag, New York, p. 138.

Campbell, G.S., 1985 : *Soil physics with Basic. Transport models for soil–plant systems*. Elsevier, Amsterdam, p. 59.

Gong, L., Xu, C., Chen, D., Halldin, S.,and Chen Y.D., 2006 : Sensitivity of the Penman–Monteith reference evapotranspiration to key climatic variables in the Changjiang (Yangtze River) basin. J. Hydrol. 329 : 620–629.

Heilman, J.L., Brittin, C.L., and Neale, C.M.U., 1989 : Fetch requirements for Bowen ratio measurements of latent and sensible heat fluxes. *Agric. For. Meteorol.* 44 : 261–273.

Howell, T.A., Evett, S.R., 2004 : The Penman–Monteith Method. *United States Department of Agriculture–Agricultural Research Service*. Conservation and Production Laboratory. www.cprl.ars.usda.gov

Kustas, W.P., Stannard, D.I., and Allwine, K.J., 1996 : Variability in surface energy flux partitioning during Washita ' 92 : Resulting effects on Penman–Monteith and Priestley–Taylor parameters. Agric. Forest Meteorol. 82 : 171–193.

Manzano, V.J.P., Mizoguchi, M., Mitsuishi, S., and Ito, T., 2011 : IT field monitoring in a Japanese system of rice intensification (J–SRI) . Paddy Water Environ. 9 : 249–255.

Mayocci, C.L., and Bristow, K.L., 1995 : Soil surface heat flux : some general questions and comments on measurements. *Agric. For. Meteorol.* 75 : 43–50.

Monteith, J.L., and Unworth, M.H., 2008 : *Principles of environmental physics*. 3rd ed. Academic Press, Burlington, MA, USA. p. 396.

Noborio, K., McInnes, K.J., Heilman, J.L., 1996a : Two–dimensional model for water, heat, and solute transport in furrow–irrigated soil : I. Theory. *Soil Sci. Soc. Am. J.* 60 : 1001–1009.

Noborio, K., McInnes, K.J., Heilman, J.L., 1996b : Two–dimensional model for water, heat, and solute transport in furrow–irrigated soil : II. Field evaluation. *Soil Sci. Soc. Am. J.* 60 : 1010–1021.

Penman, H.L., 1948 : Natural evaporation from open Water, bare soil and grass. *Proc. R. Soc. London* A193 : 120–145.

Press, W.H., Teukolsky, S.A., Vetterling, W.T., and Flannery, B.P., 1989 : *Numerical recipes in C++. The art of scientific computing 2nd ed.* Cambridge University Press, Cambridge, p. 366.

Van Bavel, C.H.M., and Hillel, D.I., 1976 : Calculating potential and actual evaporation from a bare soil surface by simulation of concurrent flow of water and heat. *Agric. Meteorol.* 17 : 453–476.

Van Bavel, C.H.M., and Lascano, R.J., 1987 : *ENWATBAL, A numerical method to compute the water loss from a crop by transpiration and evaportion*. Soil and Crop Sciences Department, Texas Agricultural Experiment Station, Texas A&M University, College Station, TX and Lubbock, TX, pp. 75.

要　　旨

蒸発散量（ET）の適切な推定は，農地におけるよりよい家畜ふん尿及び水管理を行う上で重要である．ボーエン比法や渦相関法などの微気象学的方法が ET 測定には一般的であるが，特殊な測定器や複数の測定器が必要である．一方，熱収支法による ET 推定は，簡易に入手可能な気象観測データを使って行うことができる．熱収支法を使った ET 推定値をボーエン比法による測定値と比較して評価した．岩手県盛岡市近郊にあるリード・カナリーグラス牧草畑において，短波放射量，気温，相対湿度，風速などの気象データを測定した．また，ボーエン比法測定装置も同一ほ場内に設置した．牧草キャノピー表面における熱収支式は，キャノピー温度 T_s の関数として表される．蒸発散量 E を求めるためにニュートン・ラプソン法を使って T_s についてこの熱収支式を解いた．熱収支法では，$R_n > 500\mathrm{W\ m^{-2}}$ の時に純放射量 R_n ($\mathrm{W\ m^{-2}}$) と潜熱フラックス LE（$\mathrm{W\ m^{-2}}$）をわずかに過大評価した．しかしそれ以外の時は，熱収支法で推定した R_n と LE および顕熱フラックス H ($\mathrm{W\ m^{-2}}$) は，ボーエン比法で測定したこれらの値と良く一致した．日の出から日没の間の蒸発散量の積算値を日蒸発散量として，2003 年 7 月 1 日から 7 月 28 日まで計算した．両法による日蒸発散量は，$r = 0.96$（$P < 0.001$）で非常に良く一致した．熱収支法による日蒸発散量の推定は有効であると考えられる．

キーワード：蒸発散量，ボーエン比法，熱収支法，大気射出率，作物高さ