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Evaluation of Soil Moisture Status in the Field to Improve the Production of Tanbaguro Soybeans

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1. Introduction

Tanbaguro Soybean

Tanbaguro is a generic type of soybean characterised by a black colour and large grain sizes. The weight of 100 Tanbaguro seeds is approximately 80 g, and the grains can be divided into four categories depending on the size of the grain. Namely, the grains can be classified as 3L (more than 11 mm in diameter), 2L (10 - 11 mm), L (9 - 10 mm) or M (8 - 9mm). Larger grains are preferred in certain foods such as *Nimame*, which is served during New Years celebrations. Thus, the price of large grains is relatively high. For example, 1 kg of 2L grains is often sold for more than 3,500 yen (≈35 $). Although Tanbaguro was originally produced in the Tanba area (regions of Kyoto and Hyogo prefectures), Tanbaguro is now produced in other prefectures due to the high price of large grains (Fig. 1). Tanbaguro includes many cultivars (including those released by official institutions and private companies, and those raised by the producer); however, all Tanbaguro cultivars are genetically similar (Hatanaka et al., 2008).
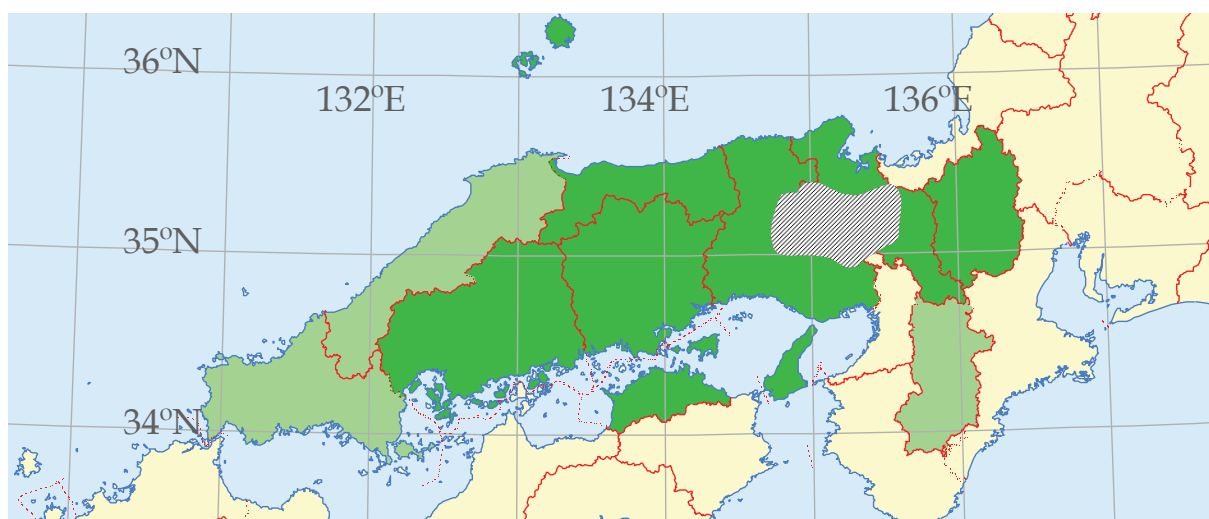

Fig. 1. Map of the Tanba area (shaded) and prefectures that produced Tanbaguro in 2006 (more than 50 t = light green; more than 100 t = green; MAFF, 2007).

After the plant is raised for 10 to 14 days in the nursery, Tanbaguro is often transplanted into the field (Matsuyama et al., 2003; Mikoshiba et al., 2009). Ridges with a height of 20 cm are prepared at 100- to 150-cm intervals, and the seedlings are transplanted to the ridges at 30- to 50-cm intervals and a plant density of 1.5 to 2.5 per m². Sparse plantings are necessary to obtain larger grain sizes.

The cultivation schedule and weather conditions of the production region are shown in Fig. 2. Because transplanting is conducted during the rainy season, water damage is often observed. After the rainy season, flowering and pod elongation occur during the summer. Thus, irrigation is one of the most important management strategies for obtaining large grain sizes and high yields. However, damage by soil born diseases such as *Phytophthora megasperma* and *Calonectria crotalariae* is common (Hinomoto, 2006) and is increased by irrigation. Thus, new strategies for water management are required.
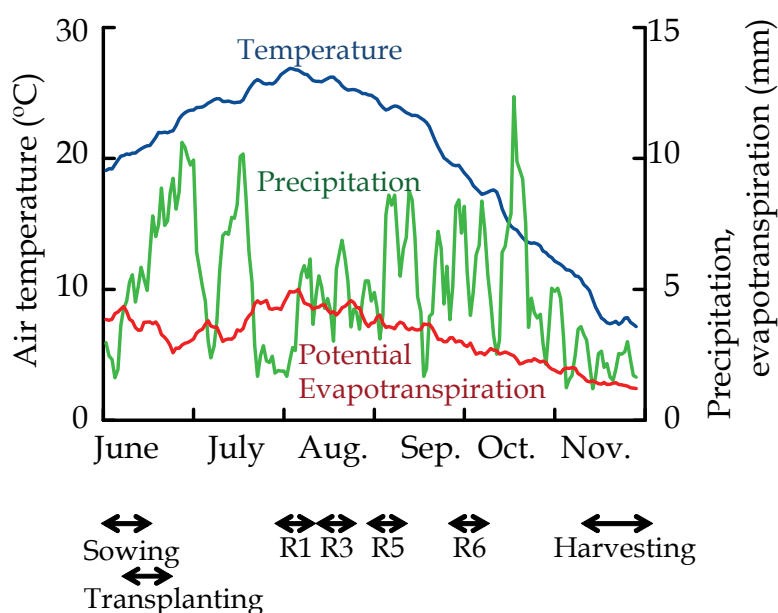

Fig. 2. Weather conditions and cultivation schedule for the production of Tanbaguro. The weather conditions are based on the 5-day-running average from 1998 to 2007 in Sonobe, Kyoto prefecture (35° 07′N, 135° 28′E). Potential evapotranspiration was estimated with the equation by Priestly & Taylor (1972). R1, R3, R5 and R6 are the developmental stages defined by Fehr & Caviness (1977) and correspond to the beginning bloom, beginning pod, beginning seed and full seed, respectively.

The present manuscript summarises the studies conducted by the author. The purpose of these studies was to provide farmers with effective and simple tools to determine the optimal timing of irrigation. To this end, three techniques were employed: (1) the use of infrared thermometers, (2) water budget simulation models and (3) the simple soil moisture meter developed by Kurose (2008).

2. Water stress index of soybean based on the difference in canopy temperature between soybean and rice

Methods for the evaluation of the plant water status based on infrared thermometers have been developed from the 1970s (Idoso et al., 1977; Jackson et al., 1981). Jackson et al. (1981)

developed the crop water stress index (CWSI), which is the most popular evaluation method and is applied to fields in the USA (Payero & Irmak, 2006). However, the canopy surface temperature and microclimate of the canopy, including the air temperature, humidity, net radiation and wind velocity, must be measured. Fields in Japan are small and widely distributed; thus, the CWSI is difficult to determine due to the cost and scale of management strategies.

Gardner et al. (1981) suggested that a well-watered plant canopy can be used as a point of reference. Although the preparation of well-watered soybean canopies is difficult, well-watered paddy fields are commonly observed in Japan. Therefore, the canopy surface temperature of rice was used as a reference (Homma & Shiraiwa, 2009). Moreover, a water stress index based on heat budget equations for soybean and rice canopies was introduced, the error of the equations was analysed, and examples of the measurements were presented.

2.1 Water stress index based on the heat budget equation (Homma & Shiraiwa, 2009)

Heat budget equations for soybean and rice canopies can be expressed by the following equations:

$$R_{nS} = H_S + \lambda E_S + G_S \tag{1}$$

$$R_{nR} = H_R + \lambda E_R + G_R \tag{2}$$

R_n is the net radiation (W m^{-2}), G is the soil heat flux (W m^{-2}), H is the sensible heat flux (W m^{-2}), λ is the latent heat of vaporisation (J g^{-1}), E is the evaporation rate (g m^{-2} s^{-1}), and subscripts of S and R represent the soybean or rice canopy, respectively. On a clear, sunny day, microclimate factors such as solar radiation and air temperature in soybean and rice canopies are similar. Namely, net radiation on soybean and rice canopies is nearly identical, and the soil heat flux is negligible compared to the net radiation (Campbell & Norman, 1998); thus

$$R_{nS} - G_S = R_{nR} - G_R. \tag{3}$$

Eqs. 1, 2 and 3 were combined to yield:

$$H_S + \lambda E_S = H_R + \lambda E_R. \tag{4}$$

Therefore,

$$\lambda (E_R - E_S) = H_S - H_R. \tag{5}$$

The sensible heat flux can be expressed by the flowing equation:

$$H_S = C_p \rho (T_{cS} - T_a)/r_{aS} \tag{6}$$

$$H_R = C_p \rho (T_{cR} - T_a)/r_{aR} \tag{7}$$

where C_p is the specific heat of air under a constant pressure (J g^{-1} °C^{-1}), ρ is the density of air (g m^{-3}), T_c is the canopy surface temperature (°C), T_a is the air temperature (°C), and r_a is the aerodynamic resistance (s m^{-1}). By substituting Eqs. 6 and 7 into Eq. 5 and assuming that the aerodynamic resistance on the soybean and rice canopy is identical ($r_{aS} = r_{aR} = r_a$), the following expression was obtained:

$$\lambda\ (E_R - E_S) = C_p\ \rho\ (T_{cS} - T_{cR})/r_a. \tag{8}$$

The latent heat flux on the rice canopy can be expressed by the following equation:

$$\lambda\ E_R = C_p\ \rho\ (e^*_{cR} - e_a)/\gamma\ /\ (r_{aR} + r_{cR}) \tag{9}$$

where e^*_{cR} is the saturated water vapour pressure at T_c (hPa), e_a is the water vapour pressure of air (hPa), γ is the psychrometric constant (hPa °C^{-1}), and r_c is the canopy resistance (s m^{-1}). After dividing both sides of Eq. 8 by $\lambda\ E_R$ and substituting Eq. 9 into the right side of the Eq. 8, the following expression was obtained:

$$1 - E_S\ /\ E_R = \gamma\ (1 + r_{cR}\ /\ r_a)\ (T_{cS} - T_{cR})/\ VPD^* \tag{10}$$

where VPD^* is the difference in the vapour pressure between the rice canopy and air:

$$VPD^* = e^*_{cR} - e_a. \tag{11}$$

Compared to field-to-field variations in the evaporation rate of the soybean canopy, that in the ratio between the canopy resistance to the aerodynamic resistance on rice canopies is relatively low ($r_{cR}/r_a \approx$ constant) because rice is cultivated under flooded conditions. Therefore,

$$1 - E_S/E_R = a\ (T_{cS} - T_{cR})/\ VPD^* \tag{12}$$

where a is a constant. In Eq. 12, if E_S is equal to E_R (water stress conditions are not observed), the index is equal to 0. Alternatively, if E_S is equal to 0 (water stress conditions exist), then the index is equal to 1. Moreover, the right side of Eq. 12 suggests that the index is proportional to the difference in the canopy temperature of soybean and rice and is inversely proportional to the difference between the water vapour pressure of the rice canopy and air. Homma & Shiraiwa (2009) set r_{cR} to 35 s m^{-1}, and r_a to 10 s m^{-1} on the basis of Homma et al. (1999) and Horie et al. (2006). Accordingly, a is equal to 3.0 hPa °C^{-1}.

2.2 Characteristics of the water stress index ($1 - E_S/E_R$)

As previously mentioned, the water stress index ($1 - E_S/E_R$) is proportional to the difference in canopy temperatures ($T_{cS} - T_{cR}$) and is inversely proportional to the difference in water vapour pressure (VPD^*) (Fig. 3). Thus, when $T_{cS} - T_{cR} = 3.0$°C, the index is equal to 0.30 and 0.22 at a VPD^* of 30 hPa and 40 hPa, respectively.

To obtain Eq. 8, we assumed that aerodynamic resistances on soybean and rice canopies were identical ($r_{aS} = r_{aR} = r_a$). When the actual relation is $r_{aS} = x\ r_{aR} = x\ r_a$, the estimation error (e.e. = estimate based on Eq. 12 – the revision based on the actual relationship) can be obtained from the following equation:

$$\text{e.e.} = \gamma\ (1 + r_{cR}/r_a)\ (T_{cS} - T_a)\ (1 - 1/x)/\ VPD^*. \tag{13}$$

The e.e. is proportional to the difference in the temperature between the soybean canopy and the air (Fig. 4a). When the actual relation is $r_{aS} = 1.1\ r_a$ at $T_{cS} - T_a = 2$°C and $VPD^* = 30$ hPa, Eq. 12 overestimates $1 - E_S/E_R$ by 0.018.

To obtain Eq. 12, we assumed that the ratio of the canopy resistance to the aerodynamic resistance on the rice canopy (r_{cR}/r_a) was constant. When the actual value of r_{cR} (r_{cR}^0) is $= x\ r_{cR}$, the e.e. can be expressed as:

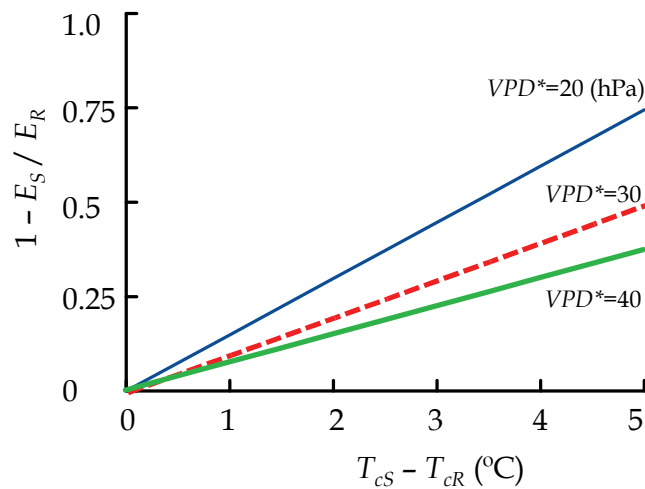$$\text{e.e.} = \gamma\ (r_{cR}/r_a)\ (T_{cS} - T_{cR})\ (1 - x)/\ VPD^*. \tag{14}$$

Fig. 3. The water stress index (1 - the ratio of the difference in evaporation between rice and soybean to the evaporation of rice: $1 - E_S/E_R$) as a function of the difference in the canopy temperature between rice and soybean ($T_{cS} - T_{cR}$) and the difference in the vapour pressure between the rice canopy and air ($VPD^* = e^*_{cR} - e_a$) (Eq. 12).
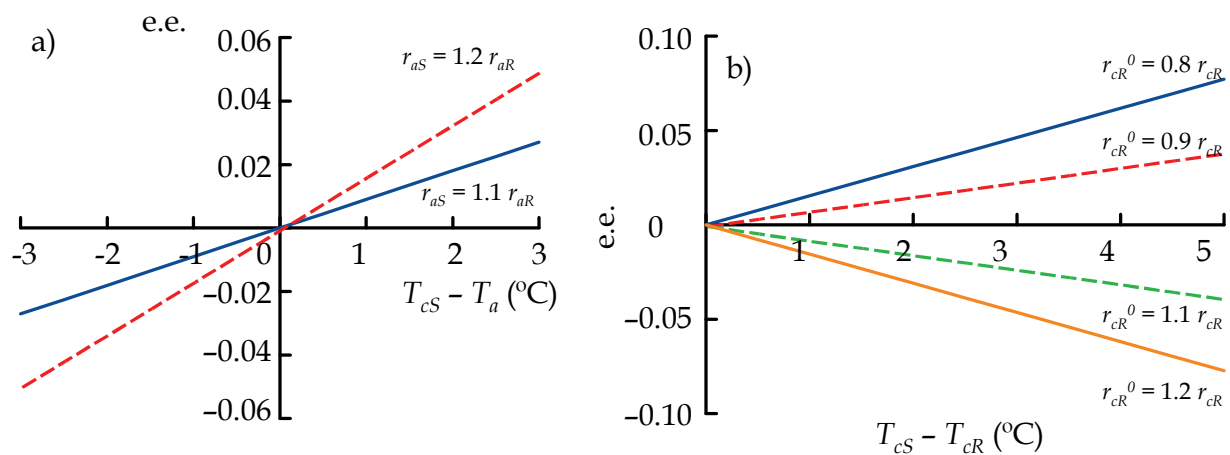

Fig. 4. Estimation error of the water stress index ($1 - E_S/E_R$) at a VPD^* of 30 hPa; (a) due to the assumption that aerodynamic resistances are the same on soybean and rice canopies ($r_{aS} = r_{aR} = r_a$; Eq. 13); (b) due to the assumption that the ratio of canopy resistance to aerodynamic resistance on rice canopies (r_{cR} / r_a) is constant (Eq. 14).

The e.e. is proportional to the difference in the canopy temperature between soybean and rice (Fig. 4b). When the actual relation is $r_{cR}^0 = 1.1 \, r_{cR}$ at $T_{cS} - T_{cR} = 3 \, °C$ and $VPD^* = 30$ hPa, Eq. 12 underestimates $1 - E_S/E_R$ by 0.023.

The water stress index is assumed to represent soybean and rice canopies under the same radiative conditions. However, net radiation is highly variable, even on a clear sunny day. Eqs. 7 and 9 were substituted into Eq. 2 to yield:

$$R_{nR} - G_R = C_p \rho \, (T_{cR} - T_a)/r_{aR} + C_p \rho \, (e^*_{cR} - e_a)/\gamma/(r_{aR} + r_{cR}). \quad (15)$$

When the net radiation and canopy temperature changes (R_{nR}' and T_c', respectively), but the air temperature and water vapour pressure do not change, Eq. 15 becomes:

$$R_{nR}' - G_R = C_p \rho \, (T_{cR}' - T_a)/r_{aR} + C_p \rho \, (e^*_{cR}' - e_a)/\gamma/(r_{aR} + r_{cR}). \tag{16}$$

Subtracting Eq. 16 from Eq. 15 yields:

$$R_{nR} - R_{nR}' = C_p \rho \, (T_{cR} - T_{cR}')/r_{aR} + C_p \rho \, (e^*_{cR} - e_{acR}^{*'})/\gamma/(r_{aR} + r_{cR}). \tag{17}$$

The relationship between $R_{nR} - R_{nR}'$ and $T_{cR} - T_{cR}'$ is shown in Fig. 5. Although the relationship is dependent on T_{cR}, changes in the T_{cR} have a minor effect on the outcome. For instance, at a T_{cR} of 35°C, a 50 and 100 W m^{-2} increase in the net radiation results in a 0.19 and 0.38°C increase in the canopy temperature, respectively. Moreover, at a VPD^* of 30 hPa, an increase in the rice canopy temperature by 0.19 and 0.38°C decreases $1 - E_S/E_R$ by 0.019 and 0.038, respectively.
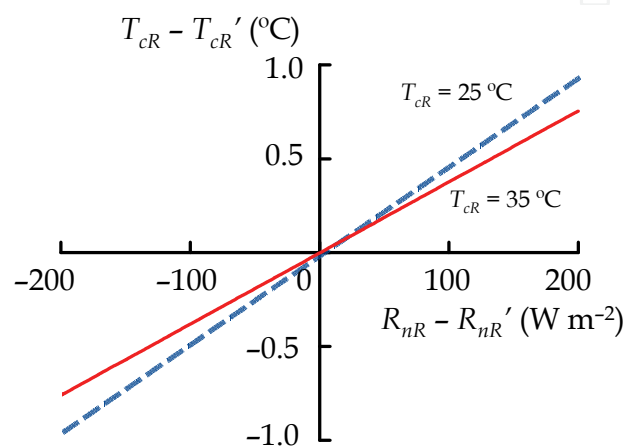

Fig. 5. The change in the surface temperature of the rice canopy ($T_{cR} - T_{cR}'$) due to net radiation ($R_{nR} - R_{nR}'$). The relationship was obtained by setting r_a and r_{cR} in Eq. 17 to 10 s m^{-1} and 35 s m^{-1}, respectively.

Consequently, compared to the value of $1 - E_S/E_R$, the error associated with the assumptions ($r_{aS} = r_{aR} = r_a$, $r_{cR}/r_a \approx$ constant and $R_{nR} = R_{nS}$) is relatively low (approximately 10%). Although the accuracy may be inadequate for the evaluation of water stress in a well-managed experiment, the estimation is valuable in the field, where simple and quick judgments are preferable over accuracy.

2.3 Example of measurements in the field

The water stress index of 35 fields in Oyugo village, Yakuno, Kyoto prefecture (35° 20′ N, 134° 56′E) was measured on August 15th and 16th of 2006, according to the proposed method. Shin-Tanbaguro soybeans (a cultivar of Tanbaguro) were planted and reached the full bloom stage (approximately 5 days after R2, according to the developmental stages proposed by Fehr & Caviness (1977)). For each soybean field, an adjacent paddy field was selected to measure the difference in the temperature of soybean and rice canopies. Koshihikari rice was planted and reached the beginning of heading. The temperature of the canopy surface was measured with a thermo tracer (TH5104, NEC Sanei Co. Ltd., Tokyo) at a depression angle of 20°. The air temperature (T_a), relative humidity (RH) and solar radiation (S_n) were measured at 5-second intervals.

The air temperature (T_a) and canopy temperature of soybean and rice (T_{cS} and T_{cR}) are shown in Fig. 6. The average ± the standard deviation of $T_{cS} - T_a$ and $T_{cR} - T_a$ was 0.71 ±

1.68°C and –1.00 ± 1.18°C, respectively. Although T_{cR} was variable, variations in T_{cR} were lower than that in T_{cS}.

To evaluate the differences in microclimate factors (C: measurement time, T_a, RH and S_n), the mean absolute error (MAE) was determined:

$$MAE = (\Sigma \mid C_S - C_R \mid) / n. \tag{18}$$

In 90 of 105 evaluations as shown in Fig. 6, T_{cR} was determined less than 1 minute before or after T_{cS}. The MAE of the measurement time was 39 seconds, and T_a and RH were nearly stable over time (Fig. 7a and b). For instance, the MAE of T_a and RH was 0.23°C and 1.6%, respectively. Although S_n was highly variable, the MAE of S_n was 50 W m^{-2} (Fig. 7c). Thus, based on the results of the aforementioned analyses, the effect of the differences in microclimate factors was minor.
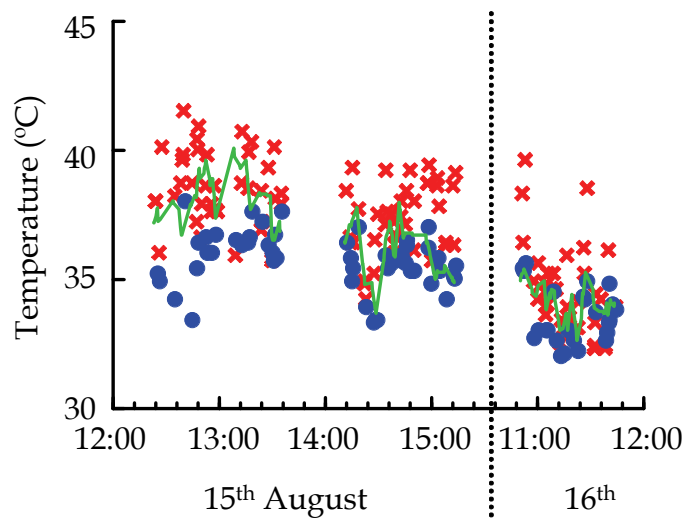

Fig. 6. Examples of measurement of air temperature (T_a: line) and canopy surface temperature of soybeans (T_{cS}: cross) and rice (T_{cR}: circle). The measurements were conducted in triplicate and were obtained from 35 fields in Oyugo village, Yakuno, Kyoto prefecture in 2006.
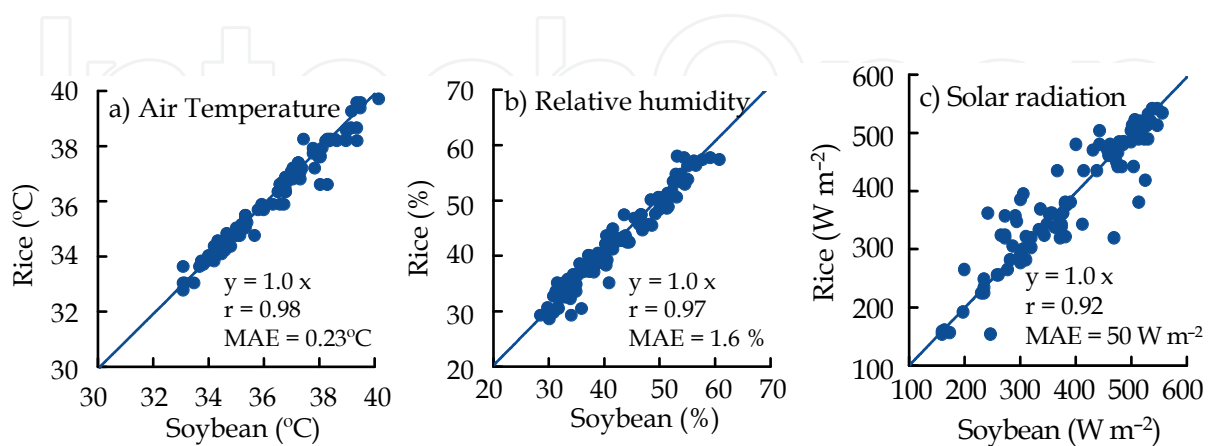

Fig. 7. The weather conditions during the measurement of the canopy surface temperature of soybean (x-axis) and rice (y-axis). MAE: mean absolute error (Eq. 18).

Date	Start	End	T_a (°C)	S_n (W/m²)	VPD^* (hPa)	$T_{cS}-T_a$ (°C)	$T_{cS}-T_{cR}$ (°C)	$1-E_S/E_R$	CWSI
15th Aug.	12:27	13:54	38.1	791	37.6	0.42	2.21	0.18	0.51
			1.0	55	3.4	1.88	1.59	0.14	0.24
	14:36	15:51	36.1	435	32.2	1.28	1.93	0.18	0.89
			1.1	144	3.5	1.51	1.07	0.11	0.36
16th Aug.	10:50	11:55	34.1	486	23.5	0.62	1.19	0.15	0.63
			0.7	236	3.5	1.37	1.17	0.13	0.26

Table 1. Summary of the measurements obtained from Oyugo village, Yakuno, Kyoto prefecture in 2006 (see Fig. 6). T_a: air temperature, S_n: solar radiation, VPD^*: vapour pressure deficit between the rice canopy and air ($VPD^* = e^*_{cR} - e_a$), $T_{cS} - T_a$: temperature difference between the soybean canopy and air, $T_{cS} - T_{cR}$: temperature difference between the soybean canopy and the rice canopy, $1 - E_S/E_R$: 1- the ratio of the difference in evaporation between rice and soybean to the evaporation of rice, CWSI: crop water stress index, as defined by Jackson et al. (1981).

The water stress index ($1 - E_S/E_R$) was compared to other water stress factors such as $T_{cS} - T_a$, $T_{cS} - T_R$ and the crop water stress index (CWSI) (Table 1). To obtain the CWSI, the definition described by Jackson et al. (1981) was applied, and the net radiation (R_n) was calculated from the S_n, T_a and T_c, according to the method of Campbell & Norman (1998). In the aforementioned calculations, the canopy resistance and the aerodynamic resistance were set to 35 s m^{-1} and 10 s m^{-1}, respectively. Differences among the measuring times were the largest for $T_{cS} - T_a$ and were the smallest for $1 - E_S/E_R$. Moreover, $1 - E_S/E_R$ was less than the CWSI. Although the CWSI was higher at the measuring time from 14:36 to 15:51 than the other times, the value of $1 - E_S/E_R$ remained relatively constant (Fig. 8). Regression lines of CWSI against $1 - E_S/E_R$ were different but not significantly among measuring times. The correlation coefficient between the CWSI and $1 - E_S/E_R$ was 0.57 ($P < 0.01$). The average of standard error of $1 - E_S/E_R$ and the CWSI for each field was 0.043 and 0.118, respectively. Thus, the results suggested that $1 - E_S/E_R$ was different from the CWSI, and more stable.
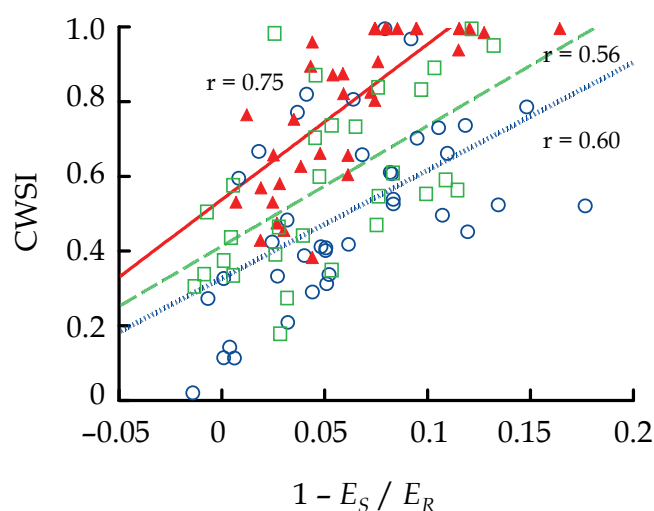

Fig. 8. A comparison of water stress indices ($1 - E_S/E_R$ and CWSI). CWSI: Crop water stress index (Jackson et al., 1981).
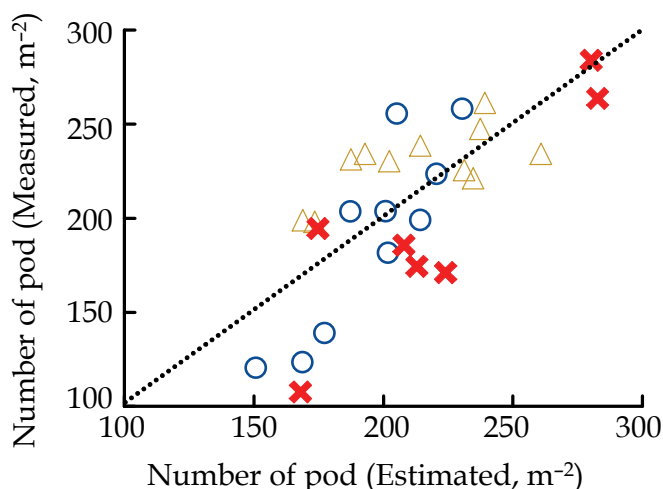
Fig. 9. The effect of water stress on the number of pods. Water stress was categorised as slight (circle; $1 - E_S/E_R = 0 - 0.15$), mild (triangle; 0.15 - 0.25) and severe (cross; greater than 0.25). Pod number was estimated by Eq. 19.

Variations in the number of pods per unit area (P) at the study site were correlated with the leaf area index (LAI; r = 0.64**) and the plant density (D; r = 0.54**) on September 12th. The multiple regression equation of P against LAI and D explained 54% of the variation in P (Fig. 9):

$$P = 21.0 \, LAI + 62.4 \, D + 15.2 \quad (R^2 = 0.54). \tag{19}$$

Soybeans with larger values of $1 - E_S/E_R$ tended to display a lower number of pods per unit area. In fields with a $1 - E_S/E_R$ greater than 0.25, the falling rate of pods (expressed as 1 – measured P/estimated P) was equal to 15%. The aforementioned results suggested that the pod set was disturbed by water stress. Moreover, the evaluation method used in the present study can be used to detect the water status of the plant.

3. Application and validation of the water budget simulation model

3.1 Water budget model

When a water budget model is applied to a farmer's field, adaptability and robustness are more important than accuracy and sensitivity. In addition, the number of parameters in the model should also be minimised. Accordingly, the water budget model developed by Ritchie (1972) was selected for the present study (Homma et al., 2008). The model is classical and has been evaluated on various occasions.

The water budget of a field can be expressed as follows (Fig. 10):

$$\Delta A_w = P_r + I_g - E_t - D_r \tag{20}$$

where A_w is the available soil water content of the root zone, P_r is precipitation, I_g is irrigation, E_t is evapotranspiration, and D_r is the drain water, which includes percolation and run off. A_w is the objective variable in the model, and E_t is determined from the following equation (Rosenthal et al., 1977):

$$E_t = E_{tp} \qquad\qquad (A_w \geq 0.3 \, AWHC)$$

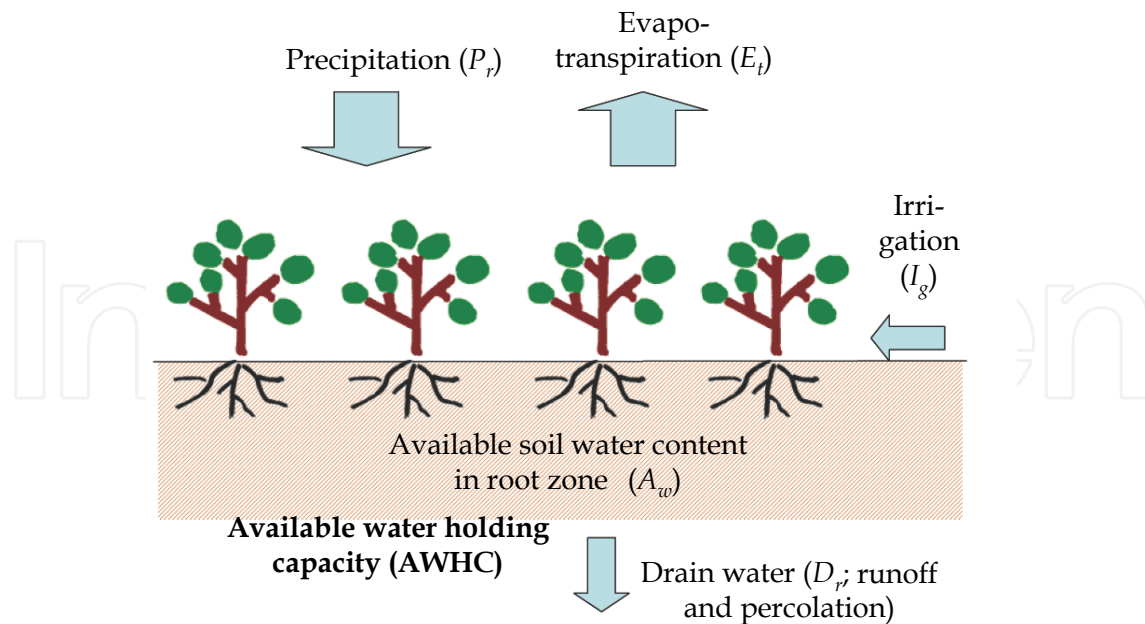$$E_t = E_{tp} \, A_w/(0.3 \, AWHC) \qquad (A_w < 0.3 \, AWHC) \tag{21}$$

Fig. 10. Schematic illustration of the water budget of a soybean canopy (Eq. 20). In the present study, the available water holding capacity (AWHC) was used as the field specific parameter of the water budget simulation model.

where E_{tp} is the potential evapotranspiration and is estimated from the daily mean air temperature and the daily amount of solar radiation (Priestly & Taylor, 1972). AWHC is the available water holding capacity of the root zone, which is a field specific parameter. According to Eq. 21, $E_t = 0$ at $A_w = 0$. However, preliminary validation results indicated that the volumetric soil moisture content (SMC) of the plough layer decreased after $A_w = 0$ because water was supplied from the subsoil. As a result, E_t did not become equal to 0. Accordingly, the following equation was added to Eq. 21 (Fig. 11):

$$E_t = 0.2\, E_{tp} \qquad (A_w < 0.06\ \text{AWHC}). \tag{21'}$$

In Eq. 21′, negative values of A_w are possible.
When A_w is larger than the AWHC, water drains from the soil, and the amount of drain water can be obtained from the following equation:

$$D_r = b\,(A_w - \text{AWHC}) \qquad (A_w > \text{AWHC}) \tag{22}$$

where b is a parameter that describes the percolation and run off capacity of the soil. The purpose of the model is to determine the optimal irrigation time; thus, the model will be applied during the summer months, when excess water ($A_w > \text{AWHC}$) is rarely observed. Therefore, b has a limited effect on the volume of drain water. As a result, the value of b was set to 0.8.
The following equation was used to convert A_w into SMC:

$$SMC = SMC_0 + A_w/\text{Sd} \tag{23}$$

where Sd is the depth of the effective soil layer. As shown in Eq. 23, SMC_0 is equal to SMC at $A_w = 0$. In the present study, A_w was converted into SMC to optimise the parameters and to validate the model.
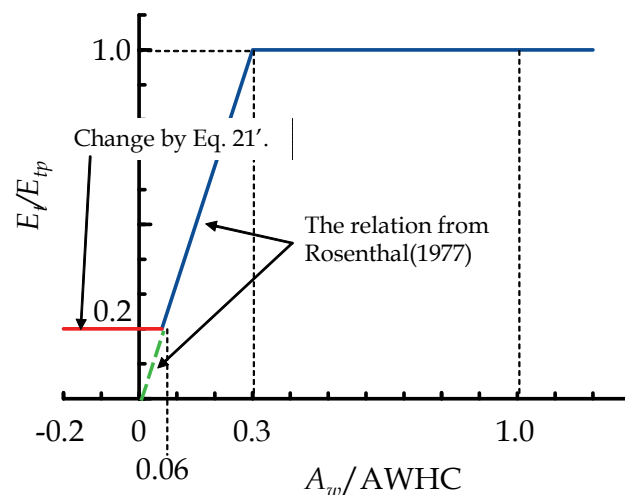
Fig. 11. Ratio of evapotranspiration to potential evapotranspiration (E_t/E_{tp}) as a function of the ratio of the available soil water content to the available water holding capacity ($A_w/$AWHC). The relationship was derived from Rosenthal (1977), and added with Eq. 21′.

3.2 Data for model validation

To validate the model, the *SMC* was obtained from several experiments associated with irrigation treatment for Tanbaguro (Homma et al., 2008). One experiment was conducted at the Kyoto Prefectural Agricultural Research Institute (Kyoto ARI; 35° 01′N, 135° 34′E) in 2007. In the experiment, PP beds (super drain bed, Co-op Chemical Co., LTD., Tokyo) were employed to control the amount of precipitation, irrigation and drainage. Four experiments were conducted in experimental fields in Kyoto ARI, Shiga Prefecture Agricultural Technology Promotion Center (Shiga ATPC; 35° 10′N, 136° 08′E), Nara Prefectural Agricultural Experiment Station (Nara AES; 34° 30′N, 135° 47′E) and the National Agricultural Research Center for Western Region (WeNARC; 34° 30′N, 133° 23′E). In these experiments, the SMC was measured with TDR soil moisture meters (EC-5, Decagon Devices, Inc., Pullman), and the data were collected with data loggers (Em5b, Decagon Devices, Inc., Pullman) at 6:00 AM every day. TDR sensors were placed at a depth of 20 cm from the top of the ridge.

In 2008, the model was applied to two farmer's fields. One field was located in Hiyoshi, Kyoto prefecture (35° 19′N, 135° 31′E), and the other field was located in Kyotanba, Kyoto prefecture (35° 11′N, 135° 25′E). Alternatively, in 2009, four farmer's fields were evaluated. One field was located in Sonobe (35° 07′N, 135° 28′E), Kyoto prefecture, another field was located in Yakuno, Kyoto prefecture and the other two fields were located in Sasayama, Hyogo prefecture (35° 04′N, 135° 14′E). The *SMC* was measured according to the aforementioned method.

For the experimental fields or PVC beds, weather data were obtained from the research institutes. Alternatively, for the farmer's fields, weather data were obtained from Japan meteorological Agency (http://www.jma.go.jp/jma/indexe.html).

3.2 Results of the validation

To reduce the error between the measured and estimated *SMC*, the simplex method, the method of nonlinear least-squares, was employed to optimise the parameters in Eq. 21 - 23

(AWHC, SMC$_0$ and Sd; Fig. 12). The results indicated that the model provided the poorest fit to the experimental data obtained from the PP beds (data not shown). Alternatively, the data obtained from the farmer's fields best fit the proposed model. Thus, irrigation treatments may disturb the uniformity of the *SMC*, and PVC greenhouses used to protect the plant from rainfall may alter evapotranspiration, which reduces the accuracy of the estimate.

Correlation coefficients between the measured and the estimated *SMC* were dependent on the AWHC (Fig. 13). The value of the correlation coefficient was extreme at a specific AWHC; however, relatively high correlation coefficients were obtained under a wide range of AWHCs. Thus, although the AWHC could not be accurately estimated, the variability in the *SMC* and A_w could be determined.
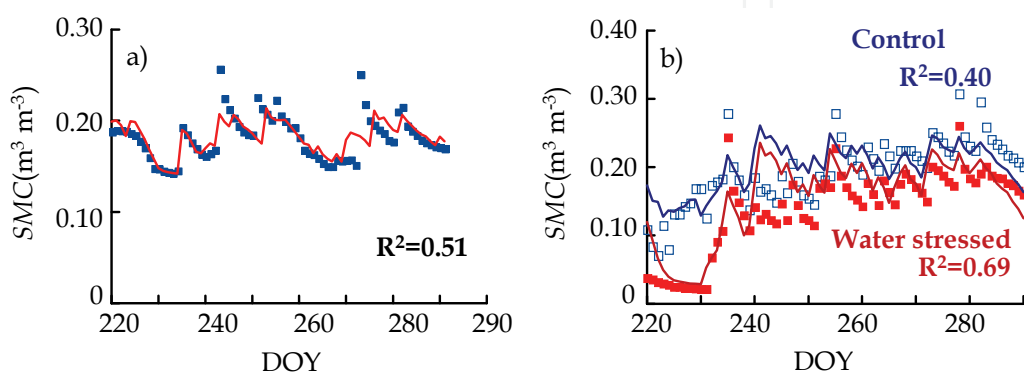
Fig. 12. Measured (symbols) and simulated (lines) soil moisture content *(SMC)* of (a) the PVC bed in Kyoto ARI and (b) the field experiment at Nara AES in 2007. DOY (Days of the Year) 213 = August 1st, 244 = September 1st.
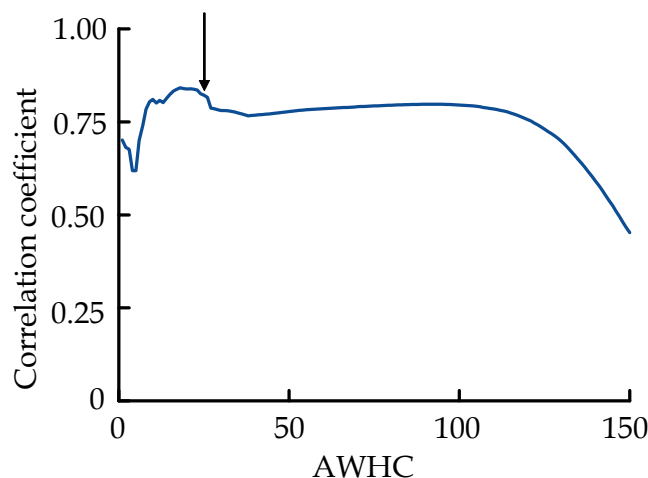
Fig. 13. The correlation coefficient between the measured and estimated *SMC* as a function of AWHC. The relationship was determined from the experiment shown in Fig. 12a. The arrows represent the set value of AWHC, as shown in Fig. 12a.

The model could accurately estimate differences in the *SMC* among irrigation treatments (Fig. 12b). The AWHC of the experimental fields varied from 34.5 to 85.9 (Table 2), and similar variations in the AWHC were observed in the farmer's fields (see Section 4). Moreover, variations in the estimated AWHC were in agreement with field observation for water holding capacity.

	n	AWHC (mm)	Sd (mm)	SMC_0 $(m^3\ m^{-3})$
Kyoto ARI	5	73.9	389	0.056
Shiga ATPC	3	44.2	241	0.066
Nara AES	8	85.9	467	0.045
WeNARC	6	34.5	332	0.247
Kyoto ARI (PVC bed)	8	33.0	588	0.095

Table 2. Estimated parameters of the water budget simulation model: available water holding capacity (AWHC), depth of the effective soil layer (Sd) and the soil moisture content at an A_w of 0 (SMC_0).

3.2 Application of the model

Because the ratio of A_w to AWHC (A_w/AWHC) is associated with the ratio of evapotranspiration to potential evapotranspiration (E_t/E_{tp}) (Fig. 11), A_w/AWHC can be used as a water stress index. As an example, the soil water conditions were evaluated during the irrigation experiment in Kyoto ARI. Based on the optimal AWHC, daily values of A_w and A_w/AWHC were calculated from the weather data (Fig. 14). As shown in Fig. 14, water stress in non-irrigated plants in the R4 to R5 growth stage was more severe than that of non-irrigated plants in the R1 to R3 growth stage because the difference between the A_w/AWHC of the control and the A_w/AWHC of plants in the R4 – R5 growth stage was relatively large. The effect of weather conditions and the AWHC was evaluated in a similar fashion (Fig. 15). As shown in Fig. 15, 2008 was a drier than 2007; however, the severity of water stress was strongly dependent on the AWHC.
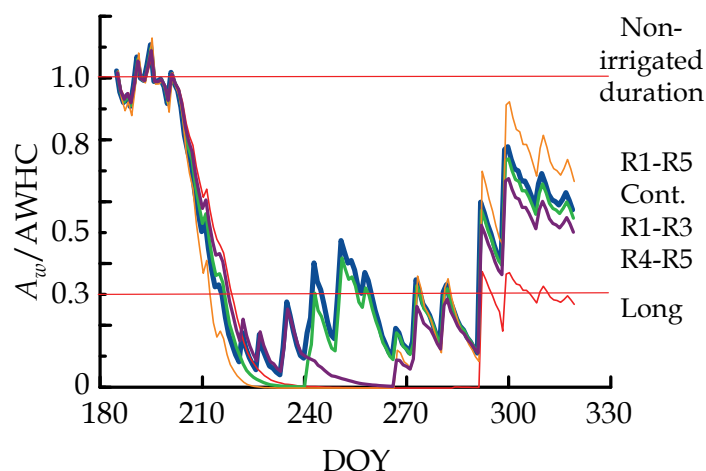

Fig. 14. Water stress conditions for the field experiment in Kyoto ARI in 2007, according to the Aw/AWHC.

A_w was solved as the objective variable of the model and was obtained in units of mm. Typically, soil moisture is expressed as the volumetric SMC ($m^3\ m^{-3}$) or gravimetric SMC ($g\ g^{-1}$) because these parameters are easier to measure. Nevertheless, to express the

relationship to plant response, *SMCs* are often converted to water potentials. However, conversion is strongly dependent on many factors such as the soil texture and soil bulk density (Hillel, 1998); thus, calibration is recommended for each field. Alternatively, the comprehensive relationship between A_w/AWHC and E_t/E_{tp} has been recognised since the 1970's, and many studies suggest that the threshold value of an A_w/AWHC is 0.3. Namely, when A_w/AWHC is less than 0.3, E_t/E_{tp} decreases linearly with a decrease in the A_w/AWHC (Fig. 11; Rosenthal et al., 1977; Loomis & Connor, 1992). In addition, by solving for A_w as the objective variable, SMC_0 and Sd, namely Eq. 23, were eliminated from the model. As a result, the model was reduced to only one parameter, and the simplicity of the model was enhanced. Namely, only the amount of water such as precipitation and evapotranspiration is considered in the simplified model (Fig. 10). Thus, the model is quite suitable for application to farmer's fields. However, A_w cannot be directly measured; thus, A_w must be estimated from the *SMC*. To apply the model to farmer's fields without measuring the *SMC*, a method for the estimation of the AWHC must be applied. Therefore, we developed the method described in the following Section (Homma et al., 2010).
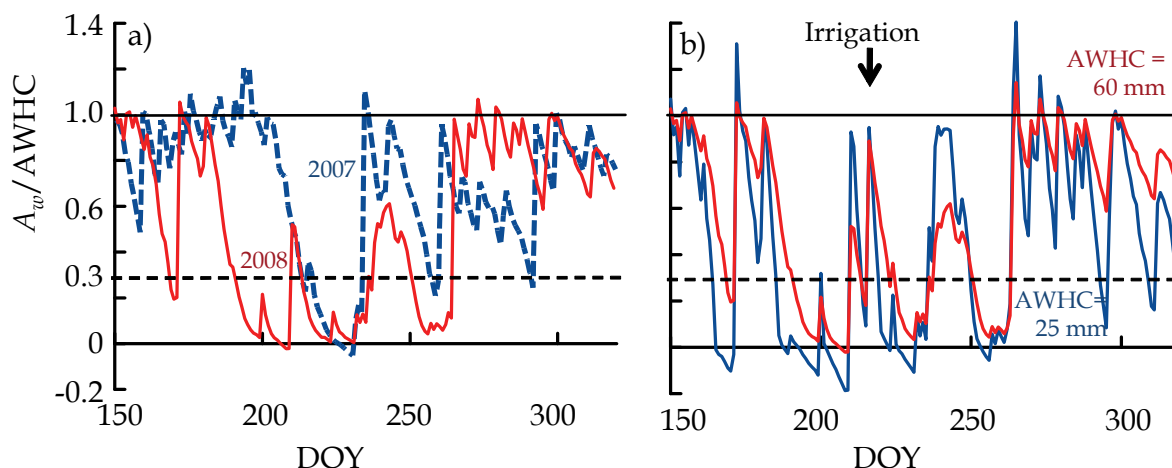

Fig. 15. The soil moisture content in Hiyoshi, Kyoto prefecture, according to the water budget simulation model; (a) fields with AWHC = 60 mm in 2007 (blue) and 2008 (red); (b) fields with AWHC = 25 mm (blue) and 60 mm (red) in 2008.

4. Estimation of the available water holding capacity (AWHC) using simple soil moisture meters

4.1 Simple soil moisture meter developed by Kurose (2008)

Kurose (2008) developed a simple soil moisture meter that can be used in farmer's fields. The fundamentals of the meter are identical to those of the ordinal soil water potential meter; however, the simple soil moisture meter contains a 1-m long clear PVC tube and does not possess a tension meter (Fig. 16). In the simplified meter, when the soil moisture becomes lower than pF 2.8, the water level in the tube decreases over time. Thus, the reduction in the water level is indicative of the accumulated water deficit, which is equal to the water deficit multiplied by the number of days. The reduction in the water level was expressed as the instrument reading (*IR*) in this study. In the present study, the initial and maximum *IR* was 0 cm and 83 cm, respectively. When the *IR* exceeds or will exceed the maximum value within one day, the meter must be refilled with water (reset). After the

meter is reset, the accumulated *IR* is obtained by combining the current *IR* and the previous *IR* (before rest). If the soil is supplied with sufficient water due to rainfall or irrigation, the *IR* approaches 0. In this case, the *IR* obtained before recovery is added to the accumulated *IR*, and the meter must be reset.
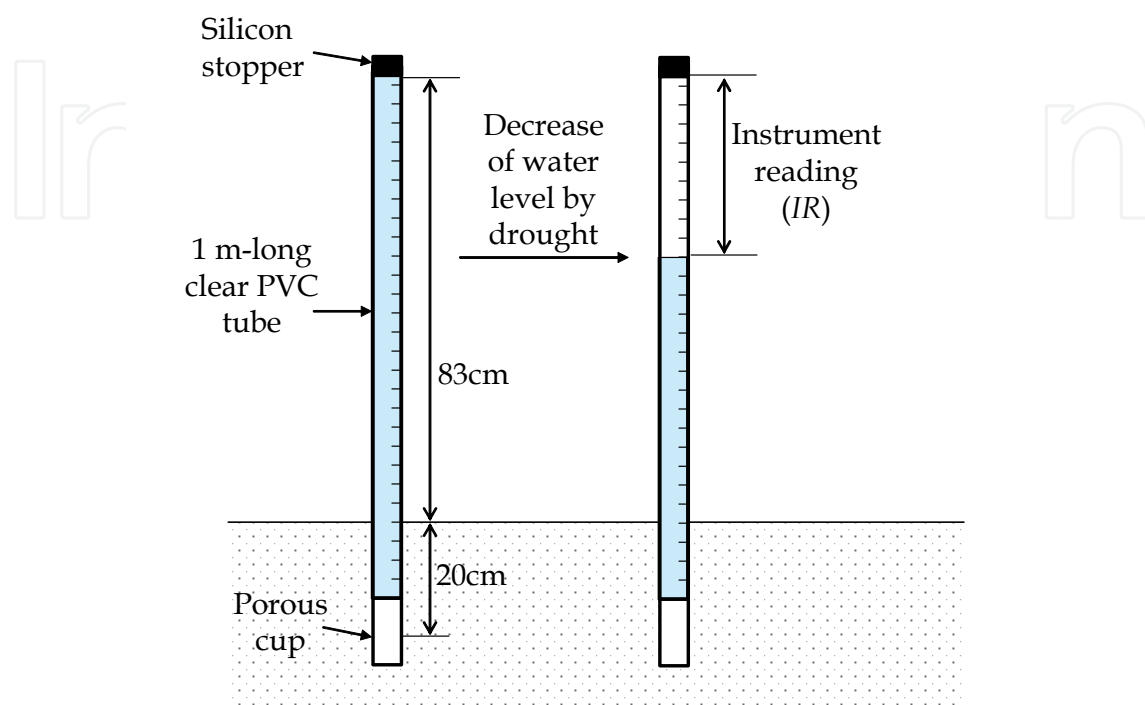

Fig. 16. Schematic illustration of the simple soil moisture meter developed by Kurose (2006). The water level in the tube decreases when soil moisture decreases below pF 2.8.

4.2 Measurements of the farmer's fields

The simple soil moisture meters were set in 15 fields in Kyotanba and 8 fields in Hiyoshi, Kyoto prefecture in 2008. The meter was vertically inserted into the top of the ridge, midway between two plants. The centre of the porous cup was adjusted to a depth of 20 from the top of the ridge. Three meters were used for each field, and the meters were inserted on July 11th. The water level of the meter was recorded 2 to 3 times per week until September 13th. Crop management practices such as irrigation and chemical application were conducted by the farmers. The date of irrigation was determined according to the authors' observation and compensated by interviews to farmers. Because the amount of irrigation was not measured, the volume of irrigation water was set to 50 mm.

In one of the 15 fields in Kyotanba and one of the 8 fields in Hiyoshi, the volumetric soil moisture content (*SMC*) was measured. TDR sensors were placed in each field, and the *SMC* was measured in triplicate according to the method described in the previous section (Section 3). Weather data were obtained from the Japan meteorological Agency (http://www.jma.go.jp/jma/indexe.html).

4.3 Estimation of the available water holding capacity (AWHC)

Similarly, the parameters in Eq. 21 - 23 (the AWHC, SMC_0 and Sd) were optimised by determining the *SMC*. The field in Kyotanba was optimised, and an AWHC of 30.5 mm, a

SMC_0 of 0.18 m^3 m^{-3} and a Sd of 223 mm were obtained, along with an R^2 of 0.53. Alternatively, an AWHC of 58.0 mm, a SMC_0 of 0.09 m^3 m^{-3} and a Sd of 387 mm was observed in Hiyoshi, and an R^2 of 0.75 was obtained. Based on the optimised parameters, the estimated *SMC* was in agreement with the actual *SMC* (Fig. 17).
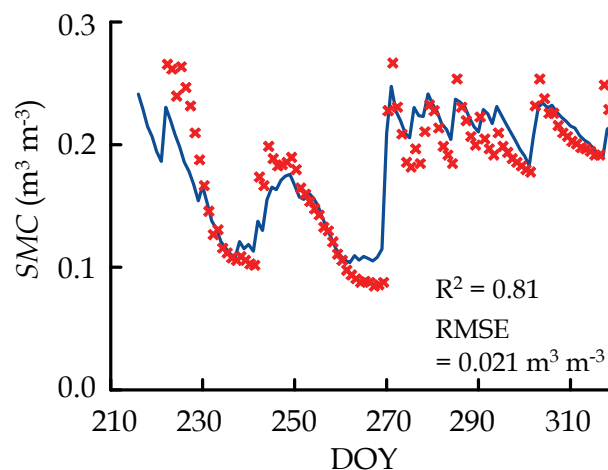

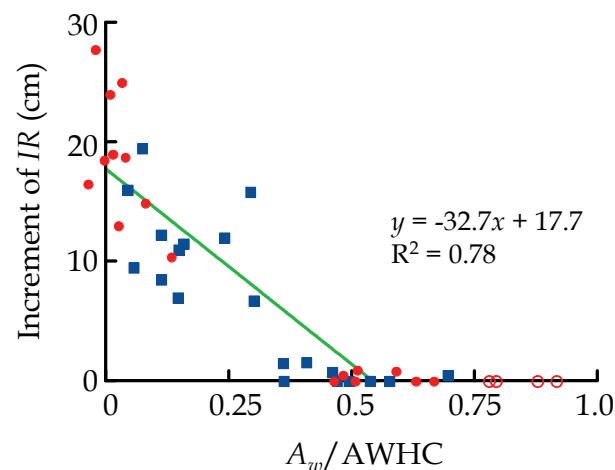Fig. 17. Measured (symbols) and simulated (lines) soil moisture content (*SMC*) in Hiyoshi, Kyoto prefecture (No. 2 in Fig. 19).

Fig. 18. The relationship between *Aw*/AWHC and the change in the *IR* of the simple soil moisture meter, which was placed in fields in Tomita (circle) and Hiyoshi (square), Kyoto prefecture. The regression equation (Eq. 20) was obtained from data with an *Aw*/AWHC lesser than 0.75.

On the basis of the optimised AWHC, daily values of *Aw*/AWHC were calculated from the weather data and were compared to the increment of *IR* per day (*ΔIR*; Fig. 18). Although the data were insufficient, *ΔIR* was almost 0 when *Aw*/AWHC was more than 0.75. Alternatively, when *Aw*/AWHC was less than 0.75, *ΔIR* increased with a decrease in the *Aw*/AWHC. Therefore, the following equation was employed to estimate the *IR*:

$$\Delta IR = -31.2 \, A_w/\text{AWHC} + 17.3 \quad (A_w/\text{AWHC} < 0.75)$$

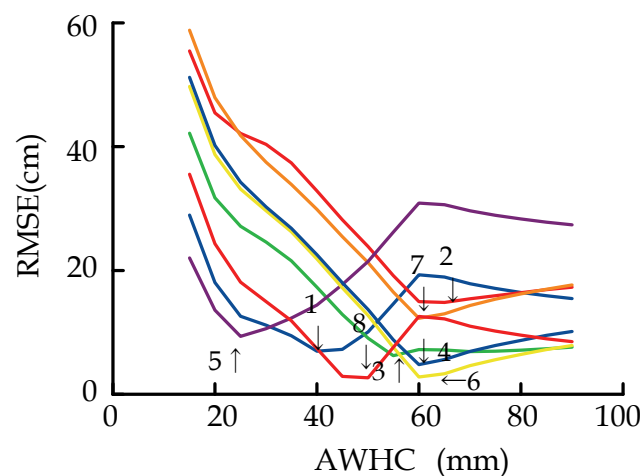$$\Delta IR = 0 \qquad (A_w/\text{AWHC} \geq 0.75). \tag{24}$$

Fig. 19. The root mean square error (RMSE) of the estimated change in the IR of the simple soil moisture meter, which was placed in 8 farmer's fields in Hiyoshi, Kyoto prefecture in 2007, according to the water budget simulation model. The error was dependent on the available water holding capacity (AWHC). When the error displayed a local minimum, the AWHC of the field was determined (arrow). The numerals on the side of the arrow represent the identification number of the field.

The AWHC was optimised by determining the sum of the least squares of error between the estimated and measured *IR*. To apply the model to the field, the AWHC must be optimised from a limited amount of *IR* data. However, if the original *IR* is inaccurate, the error is not eliminated until the meter is reset. Accordingly, we used the change in *IR* over the duration to optimise the AWHC. The change in *IR* over 1 or 2 durations did not provide a stable estimate; thus, at least three durations were necessary to achieve satisfactory results. Therefore, to estimate the AWHC, three durations were selected from the first half of the measurement (see Fig. 20). The estimated AWHC for the field in Kyotanba and Hiyoshi was 33.5 mm and 54.3 mm, respectively. These results were in agreement with those derived from the SMC (30.5 mm and 58.0 mm for the Kyotanba field and Hiyoshi field, respectively). In fields equipped with simple soil moisture meters, the AWHC was estimated from the change in *IR* over three durations (Fig. 19). As shown in Fig. 19, the difference between the measured and estimated *IR* decreased with an increase in the AWHC, until a local minimum was attained. Subsequently, the error of the *IR* increased with an increase in the AWHC. In some fields, a further increase in the AWHC resulted in a local maximum, followed by a decrease in error. Beyond the local maximum, the error of the method decreased with an increase in the AWHC due to the inherent error of the estimation (i.e.; the error became equal to the average change in *IR*, which was used in the estimate). Thus, the first local minimum was used as the value of AWHC. The estimated AWHCs varied from 24 mm to 73 mm (39.5 mm, on average) in Kyotanba and 24 mm to 61 mm (45.4 mm, on average) in Hiyoshi. These values were in agreement with the field observations of the water holding capacity and the geographical features, and enabled us to estimate the change in *IR* (Fig. 20).
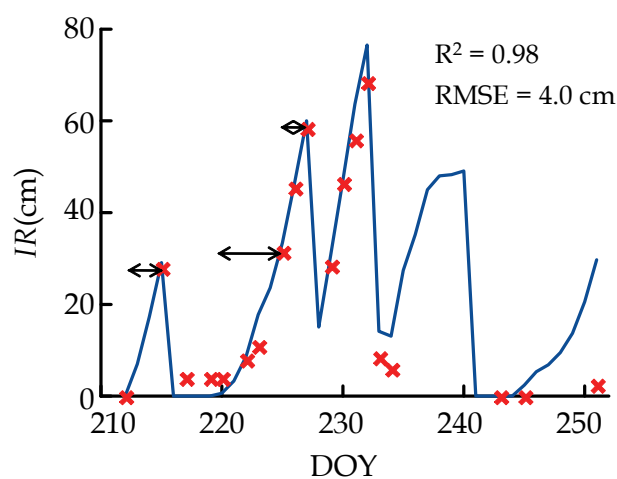
Fig. 20. The measured (symbols) and simulated (lines) instrument reading (*IR*) of the simple soil moisture meter in Hiyoshi, Kyoto prefecture (No. 6 in Fig. 19). Arrows represent the duration used to estimate the AWHC.

5. Expansion of the estimate of the available water holding capacity (AWHC) by airborne remote-sensing

To expand the study area, airborne remote-sensing was conducted to estimate the available water holding capacity (AWHC). Namely, in 2007, the temperature of the canopy surface in Sasayama was measured with a thermal airborne broadband imager (TABI, Pasco Corp., Japan) at 10:00 on August 16th. In addition, the soil moisture in 28 fields was evaluated from July 29th to September 7th with the simple soil moisture meter. All of the measurements were conducted in triplicate.
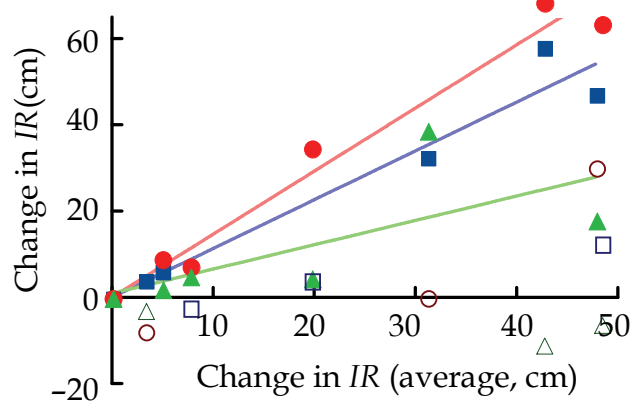

Fig. 21. The distribution of the change in instrument reading (*IR*) at each field versus the average of all 28 fields in Sasayama, Hyogo prefecture in 2007. Three of the 28 fields are shown as an example. Open symbols represent areas affected by irrigation.

Although the date and amount of irrigation must be known to estimate the AWHC from the instrument reading (*IR*) of a simple soil moisture meter, this information could not be obtained. Therefore, the timing of irrigation was determined by plotting the change in the *IR* between two consecutive measurements versus the average of the all fields (Fig. 21). In general, the *IR* change increased with an increase in the average; however, deviations from the linear relationship were observed and were likely caused by irrigation or error. To reduce the error between the measured and estimated *IR*, the AWHC was estimated after removing the observed deviations from the dataset (Fig. 22). As a result, the estimated AWHC varied from 25 to 74 mm and was geographically distributed as shown in Fig. 23a.
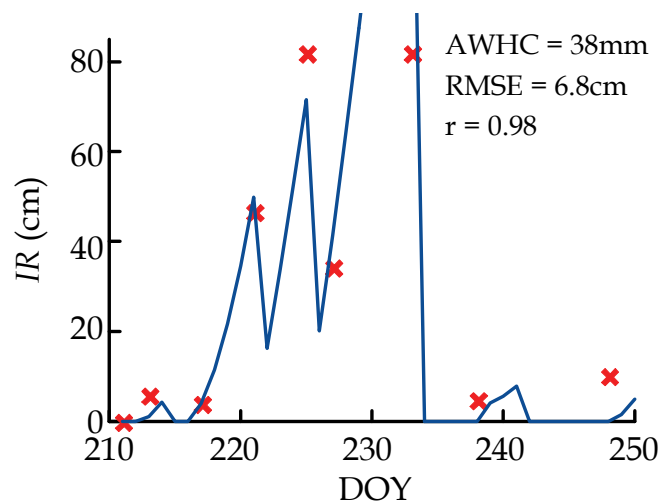

Fig. 22. The available water holding capacity (AWHC), based on the instrument reading of the simple soil moisture meter. The AWHC was determined from the root mean square error of the measured (symbol) and estimated (line) *IR*, which was obtained at the local minimum (see Fig. 19).

The estimated AWHC was weakly but significantly correlated with the canopy surface temperature (T_c) (r = 0.43, P < 0.05; Fig. 24). Moreover, changes in the *IR* over 2 days (from the 14th to the 16th of August) varied from 0 to 70 mm (Fig. 25). Twenty-three fields were normally distributed around an average *IR* of 35 cm, but 5 fields displayed *IR*s less than 5 cm and were separated from the distribution. Because the T_c of these fields was low, the fields likely received irrigation just before the T_c was measured. Upon removing the data obtained from the irrigated fields, the correlation coefficient increased to 0.59 (P < 0.01), and the following regression equation was obtained: AWHC = –3.9 T_c + 182. Using the equation, the AWHC of Tanbaguro soybean fields were estimated on the basis of the distribution of T_c, which was measured by airborne remote-sensing (Fig. 23b). As shown in Fig. 23b, geographical bias in the distribution of the AWHC was observed.
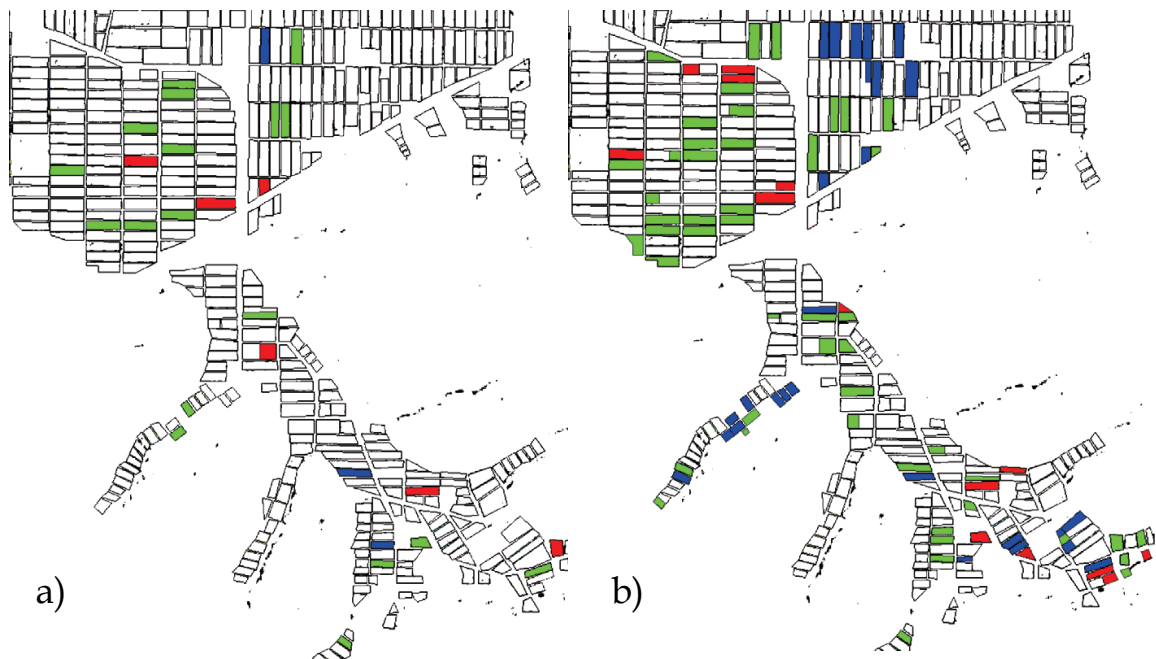
Fig. 23. The distribution of the estimated available water holding capacity (AWHC); (a) the AWHC was estimated from the results of the simple soil moisture meter, and (b) the AWHC was estimated from the canopy surface temperature. AWHC = 25 - 40 mm (red), 40 - 55 mm (green) and 55 - 74 mm (blue).
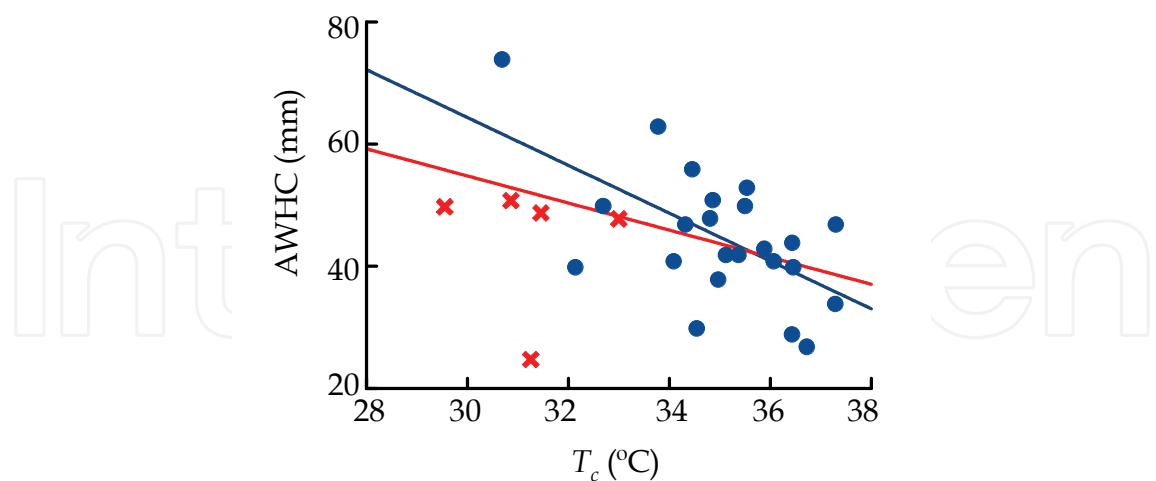

Fig. 24. The relationship between the available water holding capacity (AWHC) and the canopy surface temperature (Tc), which was measured by remote-sensing in Sasayama, Hyogo prefecture on August, 16th, 2007. Red crosses represent areas where irrigation was conducted before T_c was measured (see Fig. 25). The red line is the regression line of all of the data, and the blue line was obtained after removing data represented by red crosses.
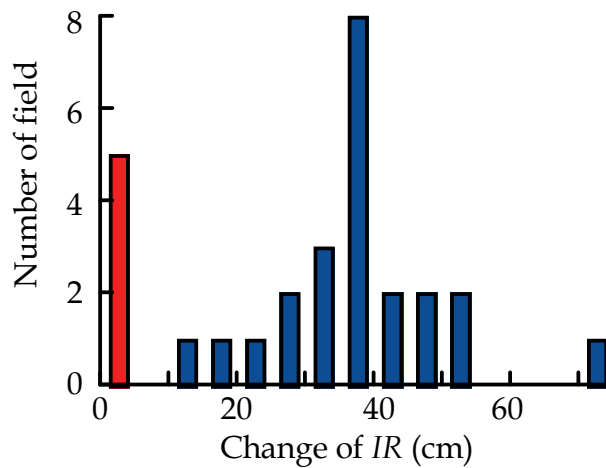
Fig. 25. Histogram of the change in the instrument reading *(IR)* of the simple soil moisture meter over 2 days (from the 14th to the 16th of August). When the change in *IR* was less than 5 cm, irrigation was likely conducted during the duration.

The measurement of T_c by air-borne remote-sensing can expand the results of the simple soil moisture meter, and the AWHC can be estimated. Because the simple soil moisture meter and the measurement of T_c were affected by irrigation, the results in the estimation of AWHC might include the effects of the amount and timing of irrigation. Thus, to accurately estimate the AWHC, the data should be obtained before the farmers conduct irrigation (before flowering).

6. Conclusions

The use of remote-sensing, water budget models and simple soil moisture meters is recommended for the evaluation of soil moisture conditions. Although the proposed methods were conducted in Tanbaguro soybean fields, the fundamental concept can be applied to other types of soybean fields or field crops. However, because the data were insufficient for the determination of the relationship between A_w/AWHC and ΔIR (Fig. 18) and the relationship between AWHC and T_c (Fig. 24), the relationships should be evaluated in future studies.

Available water (A_w) is easily accessible to plants, and the A_w zone is often greater than a depth of 1 m (Loomis & Conner, 1992). However, in the present study, the volumetric *SMC* of the plough layer (0-20 cm in depth) was used as a reference to optimise the AWHC. The *SMC* of the plough layer was obtained to reduce the complexity of the measurement; however, the relationship between A_w/AWHC and E_t/E_{tp} may have been altered (Fig. 11). Thus, although A_w/AWHC can be used as a water index, the A_w/AWHC obtained in the present study must be further evaluated. While the significance of A_w/AWHC in the present study was not determined, the estimate of the *IR* of simple soil moisture meters by the proposed method was established. The simple soil moisture meter developed by Kurose (2008) is currently promoted by official institutes such as the WeNARC. Moreover, Okai et al. (2010) reported that an *IR* greater than 80 cm leads to a significant reduction in the number of pods and the yield of Tanbaguro. Sudo et al. (2010) developed a manual for the

use of simple soil meters for the production of Tanbaguro, and recommended that the crop should be irrigated before the accumulated *IR* reaches 80 cm. By estimating the *IR*, farmers can determine the optimal timing of irrigation and improve the quantity and quality of the crop.

Recently, airborne remote-sensing has been tested in agricultural fields in Japan (Sakaiya et al., 2008). For instance, Umakawa et al. (2008) measured the T_c of Tanbaguro via airborne remote-sensing, and demonstrated that T_c and stomatal aperture were strongly correlated. Although the relationship between the AWHC and the T_{cS} measured via airborne remote-sensing was evaluated in the present study (Fig. 24), the observed relationship would be stronger if T_{cR} was used as a reference and T_{cS} was converted to $1 - E_S/E_R$. Thus, the relationship between airborne remote-sensing and the water stress index ($1 - E_S/E_R$) will be evaluated in a future study.

7. References

Campbell, G.S. & Norman, J.M. (1998) *An Introduction to Environmental Biophysics (2nd ed.).* Springer, ISBN 978-0387949376

Fehr, W.R. & Caviness, C.E. (1977) *Stages of Soybean Development. Special Report 80.* Cooperative Extension Service, Iowa State University

Gardner, B.R., Blad, B.L., Garrity, D.P. & Watts D.G. (1981) Relationships between crop temperature, grain yield, evapotranspiration and phenological development in two hybrids of moisture stressed sorghum. *Irrig. Sci.* 2, 213-224, ISSN 0342-7188

Hatanaka, T., Yoshida, S., Yagawa, M., Shibata, A., Kosaka, H. & Toda, T. (2008) The estimation of relatedness for the standardization of Tanba-guro type black soybean varieties by SSR marker. *J. Crop Res.* 53, 47-53, ISSN 1882-885X (in Japanese with English summary)

Hillel, D. (1998) *Environmental Soil Physics.* Academic Press, San Diego, ISBN 0-123-48525-8

Hinomoto, E. (2006) Problems for the stable and high quality production of Tanbaguro. *Hyogo no Norinsuisan Gijyutsu* 146, 4. (in Japanese)

Homma, K., Nakagawa, H., Horie, T., Ohnishi, H., Kim, H.Y. & Ohnishi, M. (1999) Energy budget and transpiration characteristics of rice grown under elevated CO_2 and high temperature conditions as determined by remotely sensed canopy temperatures. *Jpn. J. Crop Sci.* 68, 137-145, ISSN 0011-1848 (in Japanese with English abstract)

Homma, K., Okai, H., Ozaki, K., Kurose, Y., Doi, M., Nakai, J., Sudo, K., Ushio, A., Takeda, H., Mikoshiba, H., Shiraiwa, T. & Katsube-Tanaka, T. (2008) Development of a water balance model for "Tanbaguro" fields. *Jpn. J. Crop Sci.* 77 (Ex. 2) 132-133, ISSN 0011-1848 (in Japanese)

Homma, K. & Shiraiwa, T. (2009) Evaluation of water stress in soybean based on the difference in canopy temperature between soybean and rice. *Jpn. J. Crop Sci.* 78, 387-394, ISSN 0011-1848 (in Japanese with English abstract)

Homma, K., Okai, H., Kurose, Y., Sudo, K., Ozaki, K., Shiraiwa, T. & Katsube-Tanaka, T. (2010) Application of water budget equation model to farmer's fields of "Tambaguro" soybean. *J. Crop Res.* 55, 27-32, ISSN 1882-885X (in Japanese with English summary)

Horie, T., Matsuura, S., Takai, T., Kuwasaki, K., Ohsumi, A. & Shiraiwa, T. (2006) Genotypic difference in canopy diffusive conductance measured by a new remote-sensing method and its association with the difference in yield potential in rice. *Plant Cell Environ.* 29, 653-660, ISSN 0140-7791

Idso, S.B., Jackson, R.D. & Reginato, R.J. (1977) Remote sensing of crop yield. *Science* 196, 19-25, ISSN 0036-8075

Jackson, R.D., Idso, S.B., Reginato, R.J. &Pinter Jr., P.J. (1981) Canopy Temperature as a Crop Water Stress Indicator. *Water Resource Res.* 17, 1133-1138, ISSN 0043-1397

Kurose, Y. (2008) Method and equipment to measure soil moisture. *Patent* P07A010647, Tokyo (in Japanese)

Loomis R.S. & Connor, D.J. (1992) *Crop Ecology.* Cambridge University Press, Cambridge, ISBN 0-521-38776-0

MAFF (Ministry of Agriculture, Forestry and Fisheries, Japan) (2007) *Statistics on Crop in 2006.* Association of Agriculture and Forestry Statistics, Tokyo ISBN 978-4-541-03529-5

Matsuyama, Z., Yamashita, M., Yagasaki, K. & Sato, H. (2003) *Black Soybean (Kuro Daizu).* Rural Culture Association Japan, ISBN 978-4-540-02137-4, Tokyo (in Japanese)

Mikoshiba, H., Homma, K., Sudo, K., Ushio, A., Okai, H., Ozaki, K. & Shiraiwa, T. (2009) Analysis of production variability of soybean 'Tanbaguro'. II. Difference in yield and planting environment among 4 villages in Tanba in 2007. *J. Crop Res.* 54, 9-17, ISSN 1882-885X (in Japanese with English summary)

Okai, H., Ozaki, K. & Ashida, T. (2010) Relationship between pod set and water stress during flowering and pod elongation stage in 'Tanbaguro'. *J. Crop Res.* 55 (in press), ISSN 1882-885X (in Japanese with English summary)

Payero, J.O. and S. Irmak 2006. Variable upper and lower crop water stress index baselines for corn and soybean. *Irrig. Sci.* 25, 21-32, ISSN 0342-7188

Priestley, C.H.B. & Taylor, R.J. (1972) On the assessment of surface heat flux and evaporation using large scale parameters. *Mon. Weather Rev.* 100, 81-92, ISSN 0027-0644

Ritchie, J.T. (1972) Model for predicting evaporation from a row crop with incomplete cover. *Water Resour. Res.* 8, 1204-1213, ISSN 0043-1397

Rosenthal, W.D., Kanemasu, E.T., Raney, R.J., Stone, L.R. (1977) Evaluation of an evapotranspiration model for corn. *Agron. J.* 69, 461-464, ISSN 0002-1962

Sakaiya, E., Inoue, Y. & Fujita, M. (2008) Estimating protein content of brown rice in central Tsugaru using airborne remote sensing [2]. *Jpn. J. Crop Sci.* 77, 178-179, ISSN 0011-1848 (in Japanese with English abstract)

Sudo, K., Kawamura, H., Ashida, T., Ozaki, K., Doi, M., Shiraiwa, T., Homma, K., Katsube-Tanaka, T., Kurose, Y., Takeda, H., Mishra, K.K. & Umakawa, H. (2010) Development of decision support techniques of irrigation for stable production of black soybean on the basis of simple soil moisture meter. *Proceedings of the 169th Regular Meeting of the Society of Crop Science and Breeding in Kinki, Japan.* 26th June 2010, Faculty of Life and Environmental Sciences, Kyoto Prefectural Public University, Kyoto. P. 6.

Umakawa, H., Sudo, K., Kurose, Y., Tachibana, K., Mishra, K.K. & Shimamura, H. (2008) Measurement of water stress with airborne remote-sensing of thermal infrared. *Proceedings of the 44th Spring Conference of the Remote Sensing Society of Japan.* P. 265-268.
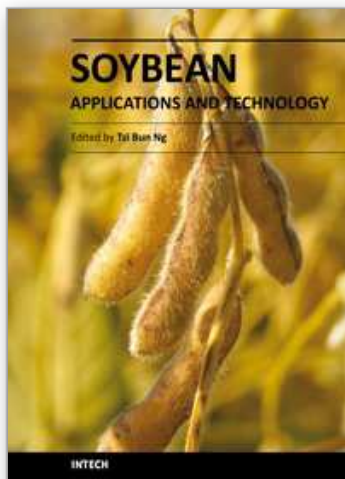
Soybean - Applications and Technology

Edited by Prof. Tzi-Bun Ng

Soybean is an agricultural crop of tremendous economic importance. Soybean and food items derived from it form dietary components of numerous people, especially those living in the Orient. The health benefits of soybean have attracted the attention of nutritionists as well as common people.

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