Measurements of the actual evapotranspiration and crop coefficients of summer and winter seasons crops in Japan

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ABSTRACT

The main goal was to understand the trends of actual evapotranspiration (AET) and crop coefficient (K_c) in summer and winter seasons crops in Japan, maize, soybean, wheat and Italian rye-grass. Bowen ratio energy balance technique (BREB) was applied to measure the AET and heat flux between ground surface and atmosphere. Measurements were carried out using an automatic weather station (AWS) installed seasonally in the experimental farm of Tokyo University of Agriculture and Technology (TUAT). Penman-Monteith equation recommended by FAO was used to calculate reference crop evapotranspiration (ET_0) and K_c was obtained from the ratio of AET to ET_0. The results indicated that the average amount of daytime AET in the winter and summer seasons crops were approximately 2.5 and 3.5 mm, respectively. Monthly daytime AET varied between 1.3 and 5.7 mm in winter season crops and between 1.4 and 6.5 mm in summer season crops. No significant differences between daily average values of AET for winter season as well as for summer season crops were found at 5% level of confidence (t = 0.9278, wheat and Italian rye-grass and t = 0.6781, soybean and maize). Average K_c values of summer season crops were found to be slightly higher than those of winter seasons crops. For planning the irrigation scheduling, it is quite necessary to understand the behaviors of AET and K_c during the growing season.

Keywords: Bowen ratio; crop coefficient; evapotranspiration; Penman-Monteith equation; agricultural crops

Actual evapotranspiration (AET) is the main path of water loss from both plant and soil surface. The main goal of irrigation is to supply plant with water as needed to obtain optimum yield and quality of a desired plant constituent. This is why in agricultural lands, AET measurement is needful for developing more efficient and sustainable water management techniques as well as for irrigation scheduling of crops (Attarod et al. 2005). To better predict actual or potential crop production, it is quite necessary to evaluate AET.

Measurement of AET from surfaces is also important for purposes such as regional water studies, field irrigation practice, description of atmospheric boundary layer and weather forecasting (Amarakoon et al. 2000).

The crop coefficient (K_c) is the ratio of AET to the reference crop evapotranspiration (ET_0) calculated by the FAO Penman-Monteith equation (Peacock and Hess 2004, Watanabe et al. 2004). ET_0 is defined as the evapotranspiration of a surface similar to a short green grass with an assumed crop height of 0.12 m, a fixed surface resistance of 70 m/s and an albedo of 0.23 (Allen et al. 1998).

K_c represents the effect of the canopy characteristics that distinguish the crop from reference surface (Peacock and Hess 2004). K_c is in a wide range in different climatic regions and crop fields and its value is definitely useful to plan the irrigation scheduling.

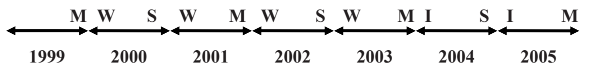
The main aim of the present study was to find out the annual trends of AET and K_c in summer season crops, soybean and maize as well as in winter season crops, wheat and Italian rye-grass in Japan.

MATERIALS AND METHODS

Study site. The measurements were conducted in the experimental farm (35°41'N, 139°29'E, 60 MSL) of the Tokyo University of Agriculture and Technology, abbreviated hereafter as TUAT, located in Fuchu city, Tokyo (Figure 1).

Experimental farm of TUAT with an area of 3 hectares examined seasonally several winter and summer seasons crops of wheat (*Triticum aestivum* L.), Italian rye-grass (*Lolium multiflorum* Lam.), soybean (*Glycine max* L. Merr.), and maize (*Zea mays* L.). The crop rotation studied in this research lasted from June 1999 until August 2005 with the following plants and schedule:

Maize (1999, 2001, 2003, and 2005)	4 years
Wheat (2000, 2001, 2002, and 2003)	4 years
Soybean (2000, 2002, and 2004)	3 years
Italian rye-grass (2004, and 2005)	2 years



Tokyo, Fuchu city, has a warm and humid climate condition with four distinct seasons. Annual average of temperature was around 20°C, with an approximate maximum of 30°C in July and August. Total yearly precipitation was around 1600 mm and fell mainly in August, September and October during the measurement period (1999–2005) (refer to Figure 2).

Measurements of AET. AET measurements were performed using the Bowen ratio energy balance method (BREB). Although this method has its own limitations, it can produce accurate results when the technique assumptions are met, and it provides continuous and unattended measurements. The BREB method measures AET by calculating the partition of convective fluxes between latent and sensible heat (Peacock and Hess 2004) based on rearranged energy balance equation described by Eq. (1):

$$\int_{t_2}^{t_1} LE = \frac{\int_{t_2}^{t_1} (R_n - G)}{1 + \beta} \qquad (1)$$

where: R_n (MJ/m^{2}d) is the net radiation at the crop surface, G (MJ/m^{2}d) is soil heat flux density, LE (MJ/m^{2}d) is latent heat flux density, β is the Bowen ratio, and the integration period (t_2–t_1) is the part of the time when the R_n was positive, i.e. approximately the hours of daytime

Therefore, in the present study, all the energy budget components were averaged in daytime. β which is the ratio of sensible heat (H, MJ/m^{2}d) to latent heat (LE) fluxes was calculated from the dry and wet-bulb temperatures measured at two different heights above the canopy coverage satisfied by Eq. (2):

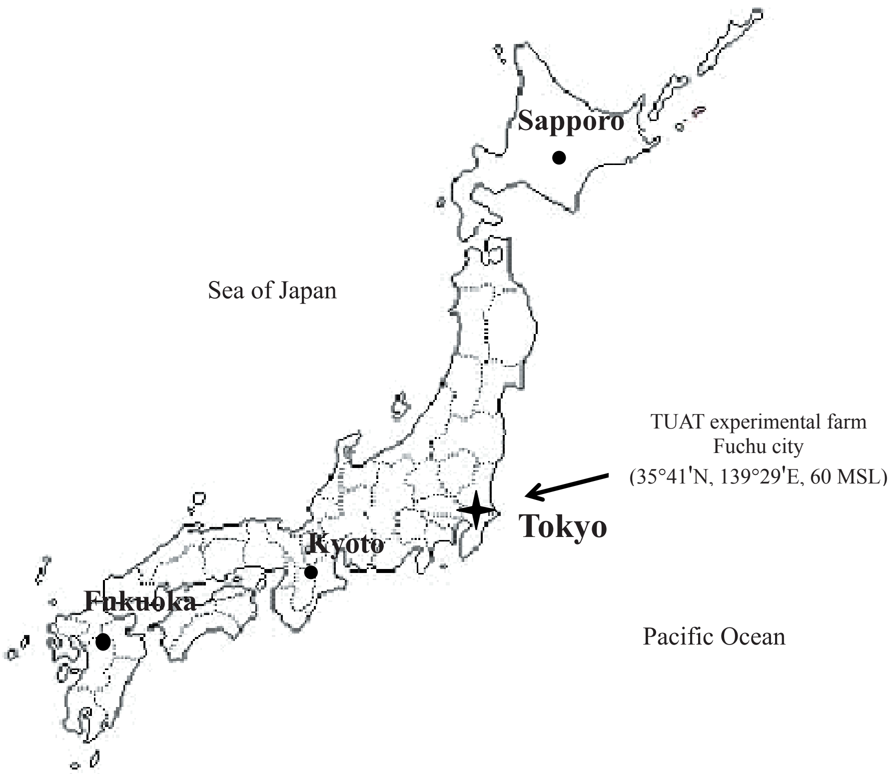


Figure 1. Location of the measurement site of the Tokyo University of Agriculture and Technology (TUAT) experimental farm, Tokyo, Japan

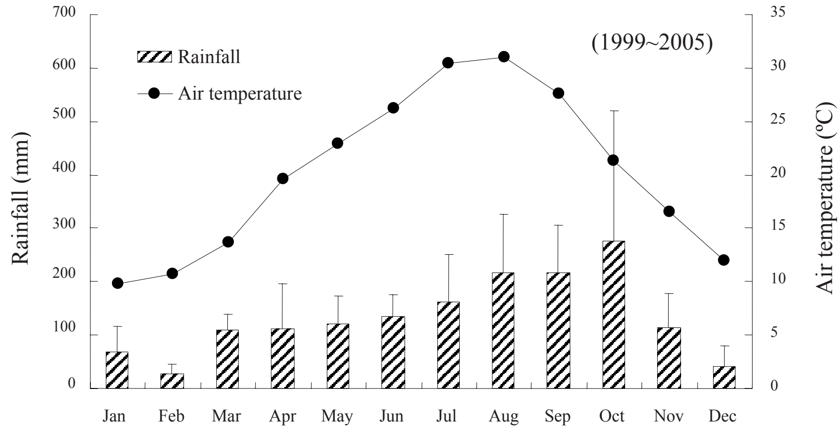


Figure 2. Monthly rainfall and air temperature of the Tokyo University of Agriculture and Technology (TUAT) experimental farm. Error bars show the standard deviations (SD) of monthly rainfall during the measurement period

$$\beta = \gamma \frac{\Delta T}{\Delta e} = \gamma \frac{T_L - T_U}{e_L - e_U} \qquad (2)$$

where: the subscripts L and U refer to the lower and upper temperatures (T_L, T_U) and vapor pressures (e_L, e_U) and γ (kPa/°C) is the psychrometric constant.

The assumptions made when using the Bowen ratio technique (Peacock and Hess 2004) are:

(1) Turbulent transfer coefficients for heat and water vapor are identical. A recent study found that the similarity theory applied in all atmospheric stability situations, thus confirmed earlier work such as Businger et al. (1971) and Crawford (1965). McNaughton and Laubach (1998), in their similarity studies, concluded that Bowen ratio technique will be satisfactory except with quite inversions.

(2) The two levels at which temperature and humidity are measured must be within the layer of the airflow adjusted to the surface so that there is an absence of horizontal gradients of temperature and humidity. This assumption is assessed by estimating required long distant fetch.

In this study, dry and wet-bulb temperatures were measured above the canopy (0.5–3 and 2.5–4.5 m) using a hand made (self-produced) 10 paired copper-constantan thermocouple thermometer (shielded and ventilated) (Figure 3).

A net radiometer (MF-11 EKO Seiki Ltd) was installed at 2–4 m above the soil surface in order to measure the net radiation flux density (R_n). The instruments were installed on a 4–6 m tower (Figure 3).

Soil heat flux density (G) was measured using two or three soil heat flux plates (P-MF-81, EKO Seiki Ltd) set up at 1 cm beneath the soil surface. Note that the installed instruments were operative just during the growing season.

Measurements were taken from the central location of the experimental farm to obtain the longest unobstructed wind fetch. TUAT experimental farm provided a uniform long-fetch location for measurement of AET which was more than 400 m (Attarod et al. 2006).

Micrometeorological measurements were observed during the growing season using automatic weather station (AWS) systems (Figure 4).

Data were collected every one minute, averaged over 10 minutes, and recorded using a data logger. All data were finally averaged into the daytime means when R_n was positive. Then daytime AET was calculated from daytime latent heat flux as AET = LE/λ, in which λ is the latent heat of vapori-

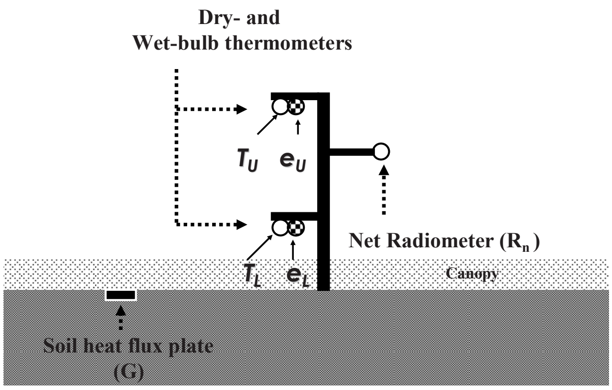


Figure 3. The simplified system to measure Bowen ratio (β), the actual evapotranspiration (AET) and micrometeorological parameters

Figure 4. Instrumentation of the Tokyo University of Agriculture and Technology (TUAT) experimental farm, the instruments installed in wheat field as a representation

zation of water (MJ/kg). The average contribution of the latent heat flux to net radiation (LE/R_n) was calculated to understand the energy allocated to the evapotranspiration process (Attarod et al. 2005).

Calculations of ET_0 and K_c. For the calculation of daily ET_0, the FAO Penman-Monteith combination equation (Allen et al. 1998) was applied using the measured meteorological data by the installed AWS. The combination equation (a universal adoption) is the preferred and reliable method for determining reference evapotranspiration worldwide (Inman-Barber and McGlinchey 2003). According to the FAO combination equation, ET_0 can be expressed as Eq. 3:

$$ET_0 = \frac{0.408\,\Delta(R_n - G) + \gamma\,[900/(T+273)]\,u_2(e_s - e_a)}{\Delta + \gamma(1 + 0.34u_2)} \quad (3)$$

where: R_n is net radiation at the crop surface (MJ/m^{2}d), T is daily mean air temperature (°C), u_2 is wind speed at the height of 2 m (m/s), e_s is saturation vapor pressure of the air (kPa), e_a is the actual vapor pressure of the air (kPa), $e_s - e_a$ is vapor pressure deficit (kPa), Δ is the slope of the vapor pressure curve at daily mean air temperature (kPa/°C) and γ is the psychrometric constant (kPa/°C) calculated as $PC_p/\lambda\varepsilon$, in which P is the air pressure (kPa) estimated as a function of altitude, C_p is the specific heat of air at constant pressure (1.013 × 10^{-3} MJ/kg/°C), λ is latent heat of vaporization of water (MJ/kg) expected as a function of air temperature at lower level of installed AWS and ε is the ratio of molecular weights of water vapor and air (0.622)

R_n was calculated using the suggested equations after Allen et al. (1998), FAO 56 method for estimating the net radiation (Goyal 2004, Maruyama et al. 2004), daily step equation.

Soil heat flux (G) was ignored beneath the hypothetical crop surface for daytime scale (Maruyama et al. 2004) since soil heat flux at the magnitude of the day below the grass reference surface is relatively small.

A logarithmic wind speed profile recommended by FAO with the observed wind speed U_z at height z was employed (Allen et al. 1998) to calculate the wind speed at 2 m above the surface (u_2).

K_c was calculated using the relation of AET/ET_0 (Watanabe et al. 2004), where AET was the measured actual evapotranspiration (mm/d) and ET_0 was the FAO reference crop evapotranspiration (mm/d).

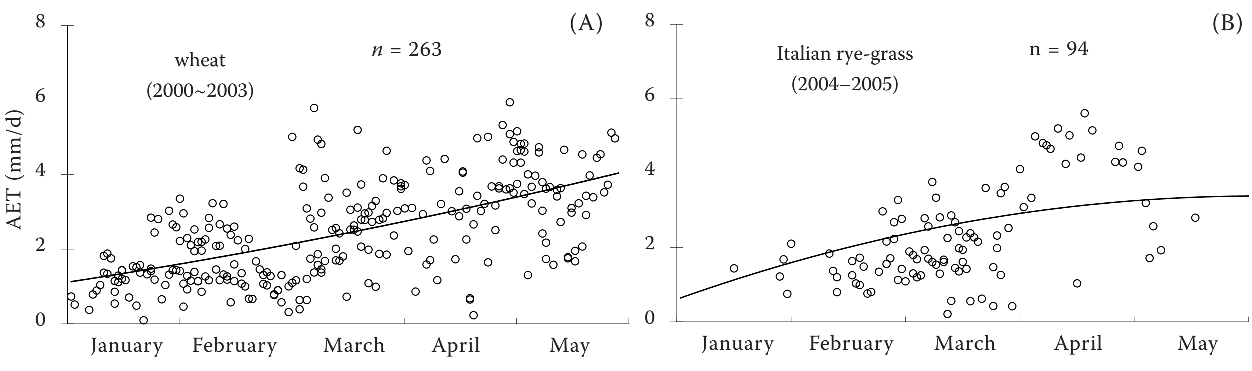


Figure 5. Changes in the daily actual evapotranspiration (AET) for winter season crops, (A) wheat and (B) Italian rye-grass from January to May (n shows the number of measured days)

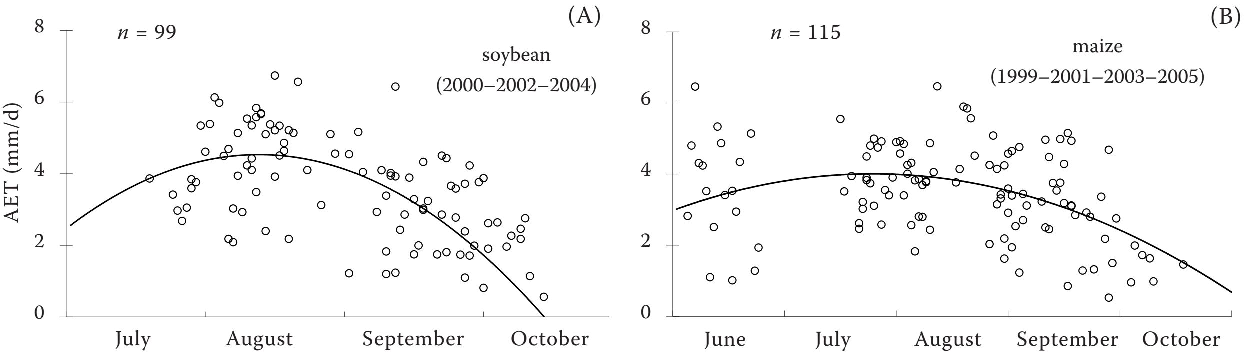


Figure 6. Changes in the daily actual evapotranspiration (AET) for summer season crops, (A) soybean; July to October, and (B) maize; June to October (*n* shows the number of measured days)

RESULTS AND DISCUSSION

Seasonal trends of AET and K_c

Seasonal trends of the measured AET for winter season crops. Figure 5 shows the changes in seasonal AET in wheat and Italian rye-grass planted in the winter season. The curves in Figure 5 were drawn statistically based on monthly mean AET. Monthly average of AET was the lowest at both sites in January (1.4 mm/d), then started to increase and reached the maximum (3.6 mm/d) in May in wheat field and in April in Italian rye-grass field (4.5 mm/d). Daily averages of AET during the growing season at both sites were the same, 2.4 mm; however, average values of LE/R_n ratio of the wheat field (57%) was higher than that of the Italian rye-grass field (50%).

Seasonal trends of the measured AET for summer season crops. Figure 6 shows the trend of AET in soybean and maize planted in the summer season. The monthly average of AET in the soybean field started to increase in July and reached the peak around the mid of the growing season that was in August (4.5 mm/d). The monthly average of AET in the soybean field was in minimum in October (0.6 mm/d).

Monthly average of AET in the maize field started to increase in June, reached the peak in July and August (3.6 mm/d), and the minimum was observed in October (1.5 mm/d). It should be mentioned that the data of June were related to the earlier planting time in the maize field (2005 data).

Daily averages of AET and LE/R_n ratio during the growing season at both sites were almost the same, 3.5 mm and 70%, respectively.

Seasonal trends of K_c for winter season crops. Figure 7 shows the trend of K_c for wheat and Italian rye-grass during the growing season. In general, monthly averages of K_c in the wheat and Italian rye-grass fields had increasing trends during the growing season, from January to May. However, low values of ET_0 at the end of January and beginning of February in the wheat field could result in high values of K_c. The monthly averages of K_c reached the maximum in May in the wheat field (0.82) and in April in the Italian rye-grass field (0.87).

Seasonal trends of K_c for summer season crops. Figure 8 shows the trends of K_c for soybean and maize during the growing season. The monthly aver-

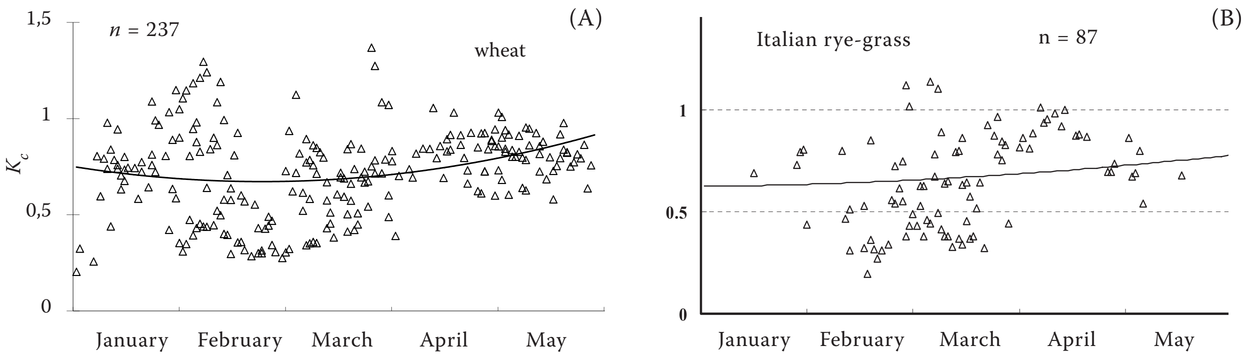


Figure 7. Changes in the daily crop coefficient (K_c) for winter season crops (A) wheat and (B) Italian rye-grass during the growing season (January to May) (*n* shows the number of measured days)

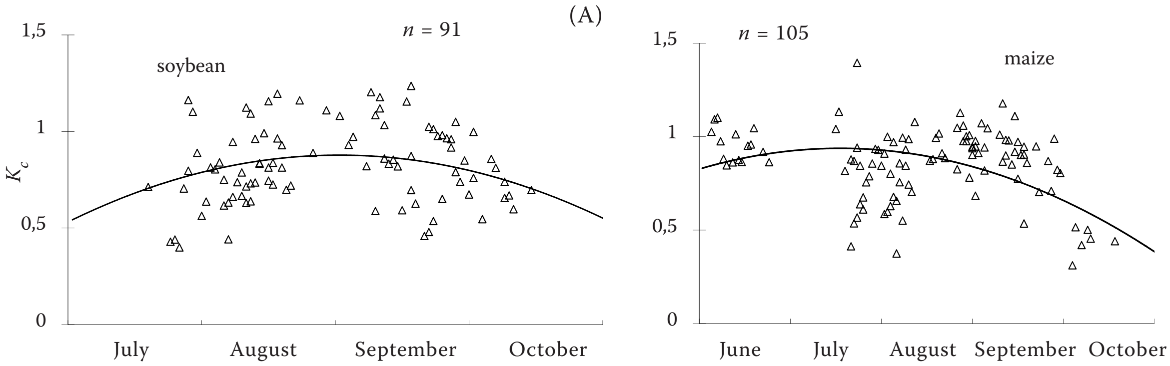


Figure 8. Changes in the daily crop coefficient (K_c) for summer season crops during the growing season (A) soybean; July to October and (B) maize; June to October (*n* shows the number of measured days)

age of K_c in the soybean field initiated to increase in July, reached the peak around the mid of the growing season in August and September (0.86) and, the minimum was observed in October (0.70).

In the maize field, the monthly average of K_c began to increase in June, reached the peak in July and August (0.84), in the mid growing season, and decreased in August and September and its minimum was observed in October (0.44 mm). The result indicated nearly the same average values of K_c during the growing season in the both sites (0.85) with approximately the same variation (SD: 0.20).

Daily averages of AET and K_c. For the period of measurement, average values of AET for wheat, Italian rye-grass, soybean and maize were found to be 2.4, 2.3, 3.6, and 3.5 mm/d, respectively, with roughly the same variations in AET at all vegetations (SD: 1.3 mm). Jorge et al. (1998) reported that the average BREB ET for the 64 measured days in a maize field planted in the experimental farm of Washington State University Irrigated Agricultural Research and Extension Center (IAREC), USA, was 4.2 ± 1.52 mm/d.

Statistical comparison of daily average values of AET for winter season as well as for summer season crops by student *t*-test at 5% level of confidence indicated no significant differences between AET values of wheat and Italian rye-grass on one hand and soybean and maize on the other (t = 0.9278 for winter season crops and t = 0.6781, for summer season crops).

Daily average of K_c for the winter season crops was between 1.2 and 0.2 and for the summer season crops it ranged between 1.2 and 0.4.

Average values of K_c in daytime for wheat, Italian rye-grass, soybean and maize were 0.72, 0.65, 0.83, and 0.85, respectively. During our measurements, all the vegetations showed approximately the similar variations in K_c (SD: 0.76).

Although student *t*-test showed a significant difference between daily mean values of K_c for winter season crops at 5% (t = 2.54), this difference was not significant at 1% level of confidence. For summer season crops, no significant difference was observed between their K_c values per daytime at 5% level of confidence (t = 1.10).

Average LE/R_n ratio for summer and winter seasons crops were found to be approximately 70% and 55%, respectively.

Conclusions

In winter season crops, AET started to increase after planting in January, and reached the peak near the end of growing season; however the peaks of AET in the summer season crops were observed in the mid growing season. Variations of AET were roughly the same in all vegetations.

Ranges of AET in the winter seasons crops, wheat and Italian rye-grass, were between 5.7 and 0.17 mm/d and in the summer season crops, soybean and maize, were between 6.5 and 0.5 mm/d. The average of daily AET in winter and summer seasons crops were about 2.4 and 3.5 mm, respectively. The results showed that maximum as well as the widest range of K_c were observed in the wheat field, 1.4 and 1.2, respectively.

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