Analyzing Evapotranspiration Components and Crop Coefficients for Catch Crop Field with Small Area at Different Plant Densities in a Greenhouse

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We cultivated dent corn as a catch crop for controlling soil salt conditions in field plots at different densities, namely, 7.3 (low), 59.7 (normal) and 119.5 (high) plants m⁻² in a greenhouse, where environmental elements and plant growth were measured for analyses of evapotranspiration components relating to the catch crop effects. Using the Penman-Monteith model with specific parameters incorporated for the crop and greenhouse, leaf transpiration and soil evaporation were estimated. Further crop coefficients were analyzed by dividing actual evapotranspiration by a reference evapotranspiration determined from meteorological data. Leaf area index for the normal and high density treatments reached 14 and 22, respectively, which were extremely high values compared to those for various other crops. Transpiration and its ratio to evapotranspiration increased with plant growth and density. Crop coefficients also increased with leaf area index and transpiration, and the coefficients for the normal and high density treatments reached high values of 1.5–2 and 2–3, respectively. These findings reveal characteristic features of plant growth and water dynamics in a catch crop field. The results of this study will contribute to the optimization of catch crop cultivation and to elucidate the crop's effects on soil salt conditions in greenhouses.

Keywords : catch crop, corn, evaporation, root absorption, transpiration

INTRODUCTION

In greenhouse horticulture, rich fertilizers are applied to soil media; however, washout events (i.e. leaching) due to rainfall do not occur. Such situations lead to the salt accumulation in greenhouse soils, and this can cause some problems for crop growth (Ono, 1999). Generally, much water is applied to soils (i.e. flooding) to transport the accumulated salts downwards from the shallower root-zone. However, this flooding induces serious environmental problems, such as ground-water pollution and nitrous oxide gas (N₂O) emission (Sadamatsu et al., 2008). Therefore, the development of environmental-friendly technologies for controlling the dynamics of soil salts is required. As one of these technologies, much attention has focused on catch crop cultivation,

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wherein the crop's roots effectively absorb salts that remain in the soil after the cultivation of major crops (e.g. Ono, 1999; Kondo et al., 2009).

For effective cultivation of the catch crops, water management should be conducted adequately based on the crop water requirement, but there has been little information about evapotranspiration and/or its components in the catch crop field. On the other hand, the effects of catch crop cultivation depend upon the characteristics of root absorption, which consist of 2 parts: (1) water absorption induced by transpiration and (2) ion absorption driven by pumps, channels, and transporters in root cell membranes (Taiz and Zeiger, 2002). Sago et al. (2011) showed that root ion absorption largely depends on water absorption. Therefore, it is essential to understand transpirational water streams as well as evapotranspiration for effective cultivation of catch crops and for evaluating crop's potential beneficial effects (Kitano et al., 2007).

In general, measuring transpirational stream (i.e. root water absorption) in hydroponic systems is relatively easy (Yasutake et al., 2009) but not in the case of soil-based culture. This is because the separation of leaf transpiration and soil evaporation is difficult; therefore, their summation evapotranspiration is usually measured by micrometeorological methods (Monteith and Unsworth, 1990). Methods for separating evapotranspiration components on the basis of micrometeorological observations have been proposed by Allen et al. (1998) and Yasutake et al. (2006). However, these micrometeorological methods have usually been used in large-scale open fields (Monteith and Unsworth, 1990) and not in greenhouses with smaller areas, except for a few examples such as Tahiri et al. (2006). Tahiri et al. (2006) estimated transpiration and evaporation in cornfields in a greenhouse by using the Penman-Monteith model and then compared them with measured values by weighing lysimeters. This method is useful because it can be applied to small soil-culture field in greenhouses, where dynamic management of water is required.

We have been developing an environmental-friendly technology using catch crops for preventing nitrate groundwater pollution and N₂O emission (Fujiwara, 2011), and have established an experimental field within a greenhouse for analyzing effective cultivation of catch crops. In this study, we applied the method used by Tahiri et al. (2006) to our experimental field, where a catch crop has been cultivated at different plant densities in a greenhouse. We individually estimated transpiration relating to root absorption and evaporation on a daily basis. Furthermore, crop coefficients, which are important parameters for analyzing and characterizing evapotranspiration components, were evaluated for the catch crop field.

MATERIALS AND METHODS

Plant material and cultivation

Dent corn (*Zea mays* L. cv. KD731) was used as the catch crop in this study. In a greenhouse (27 m × 7.7 m; N 33°33.3', E 133°40.4') at the Faculty of Agriculture, Kochi University, Japan, corn seeds were sown on 22 April, 2011, after cultivation of watermelon, at densities of 7.3 (low density, LD), 59.7 (normal density, ND), and 119.5 (high density, HD) plants m⁻² in field plots (8 m × 1 m). Three plots for each density, and 3 additional plots for no plant, were located randomly in the greenhouse, as shown in Fig. 1(a). The plant density value for the ND treatment corresponded to that described by Ohdan and Daimon (1998), and the value for the LD treatment was in the normal range for cornfields (e.g. Tahiri et al., 2006; Yasutake et al., 2007). The corn was harvested on 10 June, after a growing period of only 50 days. This period was shorter relative to normal corn cultivation practices (e.g. Yasutake et al., 2007) but was reasonable from the view point of catch crop cultivation during a fallow term in greenhouses (Inoue et al., 2010). During the growing period, 3–5 mm of water was applied to the plots every day using a drip irrigation system, and the total amount of irrigated water was 183 mm.

Measurements

Environmental elements in the greenhouse, such as solar radiation (R_s), net radiation (R_n), air temperature (T_a), air relative humidity (RH), wind speed (u), and ground heat flux (G) were measured and recorded on the data logger (NR-600, KEYENCE, Japan) automatically at 5 s intervals. Table 1 summarizes the instruments used for measuring these environmental elements. The sensors for solar radiation, air temperature, air humidity, and wind speed were installed around the center of the greenhouse (Fig. 1(a)). Heights for the air temperature/humidity sensor and the anemometer were changed to an upper position on 25 May due to the increase in plant height. In the LD-3, ND-2, and HD-1 plots, the net radiation sensor was set 0.2 m above the canopy by taking into consideration for the sensor's response to the angle of incidence (Kipp & Zonen, 2004); the ground heat flux sensor was buried into the soil at a depth of 0.05 m for analyzing the energy balance of the crop canopy at different densities (Fig. 1(a), (b)). The volumetric water content of the soil at the depth layer from 0.05 m to 0.10 m was measured using a portable instrument (STE; Decagon Devices Inc.) immediately prior to the irrigation event at 1800–1900 h every day.

Plant height (h) and length (L), width (W) of all leaves of 3–5 plants for the 3 treatments were directly measured at intervals of 3–7 days. The area (A) of a leaf was estimated using the equation $A = 0.78LW - 4.93$ (determination coefficient $r^2 = 0.99$), which was derived from parameters obtained in a preliminary experiment. In the experiment, a relationship of L and W with A for 126 corn leaf samples was determined using an automatic area meter (AAM-9; Hayashi Denko Inc., Tokyo). The leaf area index (LAI) was calculated from the leaf area (LA) of a single plant and plant density.

Reference crop evapotranspiration

Environmental elements such as radiation, air temperature, humidity, and wind speed, etc. induce evaporative demand to crop fields (Kitano et al., 1990). As an index of the evaporative demand, reference crop evapotranspiration (ET_0), which is determined as evapotranspiration from a well-watered reference grass surface, is frequently used. It is calculated using the FAO Penman-Monteith equation (Allen et al., 1998):

$$ET_0 = \frac{0.408 \Delta (R_n - G) + \gamma \frac{900}{T_a + 273} u (e_s - e_a)}{\Delta + \gamma (1 + 0.34u)} \quad (1)$$

where e_s is the saturation vapor pressure at T_a , e_a is the actual vapor pressure, Δ is the slope of the vapor pressure curve, and γ is the psychrometric constant. In this study, ET_0 was obtained using the mean value of daily R_n s for the LD-3, ND-2, and HD-1 plots. And air temperature/humidity and wind speed were measured at a height of 2.60 m until 24 May, and then at 3.15 m after 25 May. Since the cumulative ground heat flux during the day was relatively small, G was ignored in this analysis.

Analyzing transpiration, evaporation, and crop coefficients

Daily transpiration rate (Tr) and evaporation rate (E) were analyzed separately using the

Table 1 Instruments used for measuring environmental elements in the greenhouse.

Environmental element	Instrument	Height
Solar radiation	CHF-LP02, Hukseflux	4.00 m
Net radiation	CPR-NR-LITE, Kipp & Zonen	0.20 m above the canopy
Air temperature	CVS-HMP-60, Vaisala	2.65 m → 3.15 m ^a
Air relative humidity	CVS-HMP-60, Vaisala	2.65 m → 3.15 m ^a
Wind speed	V-01-AND2L, Ai-Denshi-Giken	2.55 m → 3.15 m ^a
Ground heat flux	CHF-HFP-01, Hukseflux	−0.05 m

^a Heights for the air temperature/humidity sensor and the anemometer were changed to an upper position on 25 May due to the increase in plant height.

Fig. 1 Schematic diagrams of cultivation design in the greenhouse (a) and a field plot equipped with an elastic pole for the net radiation sensor (b): ×, solar radiation sensor; ○, air temperature and relative humidity sensor; □, wind speed sensor; △, net radiation sensor and ground heat flux sensor.

Penman-Monteith model with specific parameters incorporated for corn canopy (Tahiri et al., 2006). Tahiri et al. (2006) applied this model to a cornfield in a greenhouse and estimated Tr and E with a high accuracy. Tr was calculated from Eq. (2):

$$Tr = \frac{\Delta(R_N - R_N') + (C_p \rho / r_A)(e_s - e_A)}{\Delta + \gamma(1 + r_c / r_A)} \quad (2)$$

where R_N' is the net radiation reaching the soil surface, $C_p \rho$ is the volumetric heat capacity of air, r_A is the aerodynamic resistance of the canopy, and r_c is the internal resistance of the canopy. An equation for estimating R_N' was derived by Uchijima (1976):

$$R_N' = [\exp(-0.622LAI + 0.055LAI^2)]R_N \quad (3)$$

Eq. (3) seems to be most effective when LAI is less than 5. However, Kimura et al. (2011) reported that the LAI value for corn canopy as a catch crop far exceeded the threshold value ($LAI=5$), indicating that Eq. (3) cannot be applied to this crop. In this study, R_N measurement was made just above the canopy and the soil surface in advance, and then the following equation was used for estimating R_N' in the canopy:

$$R_N' = [-LAI / (2.43 + LAI) + 1]R_N \quad (4)$$

The parameters r_A and r_c in Eq. (2) can be obtained from the LAI , the heat transfer coefficient for individual leaves, and the stomatal resistance, etc. (Tahiri et al., 2006). Procedures for determining these parameters have been described in detail by Bailey et al. (1993), Farahani and Bausch (1995), and Gardiol et al. (2003).

For estimating E in the field plots, we made the following assumptions: (1) that the soil was wet enough for evaporation to occur at the maximum rate and to be limited only by energy availability at the soil surface, and (2) that the wind speed under the canopy was negligible due to the extremely low value. Under these situations, E can be estimated using Eq. (5) (Tahiri et al., 2006):

$$E = \frac{\Delta(R_N' - G)}{\lambda(\Delta + \gamma)} \quad (5)$$

The crop coefficients and related parameters, which are used for expressing evapotranspiration and its components on a daily basis (Allen et al., 1998; Yasutake et al., 2007), were analyzed using Eqs. (6) to (8):

$$K_{cb} = Tr / ET_0 \quad (6)$$

$$K_e = E / ET_0 \quad (7)$$

$$K_c = (Tr + E) / ET_0 = ET / ET_0 = K_{cb} + K_e \quad (8)$$

where K_{cb} is the basal crop coefficient, K_e is the evaporation coefficient, K_c is the crop coefficient, and ET is the actual evapotranspiration value.

RESULTS AND DISCUSSION

Figure 2 shows the daily changes in R_s , R_N , T_A , RH , u , and ET_0 in the greenhouse during the growing period (22 April to 11 June, 2011). R_s varied due to weather conditions but was approximately $20 \text{ MJ m}^{-2} \text{ d}^{-1}$ on fine days. R_N changed in parallel with R_s and was $10\text{--}13 \text{ MJ m}^{-2} \text{ d}^{-1}$ on fine days. T_A gradually increased with time, and the average value during the growing period was 22°C . RH also appeared to increase over time, ranging between 45% and 90%, which can be attributed to the atmospheric humidity conditions (data not shown) and plant growth (see Fig.3). The average RH was 70%. The value of u changed at an extremely low level due to the steady greenhouse conditions (Yasutake et al., 2011) and was consistently less than 0.15 m s^{-1} . The ET_0 calculated from Eq. (1) using R_N , T_A , RH , and u had a similar variation pattern to that of R_N , and it fluctuated between 0.01 mm d^{-1} and 4.2 mm d^{-1} . The average ET_0 during the whole growing period was 2.3 mm d^{-1} .

Figure 3 shows the daily changes in h , LA , and LAI of catch crop plots at the different plant densities (LD, ND, and HD) during the growing period. There was no considerable difference in h among the 3 plots for the majority of the growth period; however at the harvest on 11 June, h reached 200 cm in the LD treatment but remained 160–170 cm in the ND and HD treatments. The h values obtained in this study were remarkably higher than those from an open-air cornfield study (Yasutake et al., 2007). This may be due to differences in the growth environments. The effects of plant density on LA gradually became apparent 25 days after sowing onwards, and LA in the LD treatment was about 3 times that in the ND and HD treatments at the harvest time. In the ND and HD treatments, expansion of leaf area may be suppressed by shade due to the extremely high plant

Fig. 2 Daily changes in integrated solar radiation (R_s), integrated net radiation (R_N), mean air temperature (T_A), mean relative humidity (RH), mean windspeed (u), and integrated reference crop evapotranspiration (ET_0) in the greenhouse during the growing period (22 April to 11 June, 2011).

Fig. 3 Daily changes in plant height (h), leaf area of a single plant (LA), and leaf area index (LAI) of catch crop field plots with low (LD), normal (ND) and high (HD) plant densities during the growing period (22 April to 11 June, 2011).

densities (Bos et al., 2000). A different pattern of LAI was found among the 3 plots, as LAI was lowest in the LD treatment and highest in the HD treatment. Since LA was characterized as mentioned above and LAI was evaluated from both LA and plant density, the pattern of LAI should reflect the differences in plant density. LAI in the LD treatment reached about 5 at the harvest, and this value corresponded to the maximum values observed by Tahiri et al. (2006) and Yasutake et al. (2007). On the other hand, LAI values at the harvest were 14 and 22 in the ND and HD treatments, respectively, which are extremely high compared with those of various other crops, such as rice (Stroppiana et al., 2006), wheat (Kang et al., 2005), and soybean (Choi and Inoue, 2004). The high value of LAI seems to be a characteristic feature in catch crop cultivation with high plant density.

Figure 4 shows the daily changes in Tr , E estimated from Eqs. (2) and (5), and their summation ET for the LD, ND, and HD catch crop plots. Generally, at an early stage when ground cover was relatively low, E was much larger than Tr , and this continued until approximately 30, 20, and 15 days after sowing for the LD, ND, and HD treatments, respectively. At a later stage when most of the field was covered with corn leaves, Tr accounted for a large part of ET , as has been well-observed in crop fields (e.g. Liu et al., 2002).

For the LD treatment (Fig. 4(a)), cumulative Tr and E during the growing period were 40.9 mm and 78.3 mm, respectively, corresponding to 34% and 66% of the cumulative ET (119.2 mm). The Tr/ET ratio (0.34) obtained in this study lay between those obtained by Kang et al. (2003) and Yasutake et al. (2007). This method was applied to the ND and HD treatments with higher LAI values. Cumulative Tr and E values for the ND treatment were 102.6 mm and 50.9 mm, and their ratios to ET (153.5 mm) were 67% and 33%, respectively (Fig. 4(b)). For the HD treatment (Fig. 4(c)), cumulative Tr (137.9 mm) and E (43.2 mm) accounted for 76% and 24% of ET (181.1 mm). These results indicate that the increase in plant density associated with LAI induced increases in ET and in the ratio of Tr to ET in the plots which were irrigated with 183 mm of water during the growing period. The amount of water irrigated and the amount lost due to evapotranspiration were approximately equal in the HD treatment, but a larger difference between them was observed in the ND and LD treatments. This may be attributed to the downward water flow (infiltration) in the field soil. Further research is required to analyze the water balance of the field plots in detail.

Figure 5 shows the daily change in crop coefficients K_{cb} ($=Tr/ET_0$), K_e ($=E/ET_0$), and K_c ($=K_{cb}+K_e$) of catch crop plots for the LD, ND, and HD treatments. Similar to the trends observed for Tr and E in Fig. 4, K_e was higher than K_{cb} and remained relatively constant around at 1 during the

Fig. 4 Daily changes in transpiration (Tr), evaporation (E), and evapotranspiration ($ET=Tr+E$) of catch crop field plots with low (LD), normal (ND) and high (HD) plant densities during the growing period (22 April to 11 June, 2011).

early growth stage because of the lower level of ground cover and the wet-surface soil due to daily irrigation. Subsequently, the reverse relationship gradually became apparent as K_{cb} increased closer to K_c . For the LD treatment, the K_c value was approximately 1 at the time of harvest, consistent with previous reports (Allen et al., 1998; Kang et al., 2003). In contrast, the K_c values for the ND and HD treatments were 1.5–2 and 2–3, respectively. These extremely high values suggest that water requirements are greater for catch crop cultivation than for other crops because of high LAI (Fig. 3), and therefore, specific water management is required for catch crop cultivation practices.

Thus, leaf transpiration and soil evaporation were estimated separately and further crop coefficients were analyzed in catch crop fields with small area (plots) in the greenhouse. The information obtained in this study will contribute to the development of effective catch crop cultivation and to the analysis of crop's effects on salt conditions in soils.

Fig. 5 Daily changes in the basal crop coefficient (K_{sb}), soil evaporation coefficient (K_e), and crop coefficient ($K_c=K_{sb}+K_e$) of catch crop field plots with low (LD), normal (ND) and high (HD) plant densities during the growing period (22 April to 11 June, 2011).

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