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Tomato and cowpea crop evapotranspiration in an unheated greenhouse

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Abstract: With the development of protected cultivation of vegetables in China, it is necessary to study the water requirements of crops in greenhouses. Lysimeter experiments were carried out to investigate tomato (2001) and cowpea (2004) crop evapotranspiration (ET_c) in an unheated greenhouse in Eastern China. Results showed remarkably reduced crop evapotranspiration inside the greenhouse as compared with that outside. ET_c increased with the growth of the crops, and varied in accordance with the temperature inside the greenhouse and 20-cm pan evaporation outside, reaching its maximum value at the stage when plants' growth was most active. Differences between the variation of crop evapotranspiration and pan evaporation inside the greenhouse were caused by shading of the pan in the later period when the crops were taller than the location where the pan was installed, 70 cm above ground. The ratio of crop evapotranspiration to pan evaporation was not constant as reported in previous studies, and the variation of the inside ratio α_{in} lagged behind that of the outside ratio α_{out}. Simulation of crop evapotranspiration based on 20-cm pan evaporation inside the greenhouse is more reasonable than that based on 20-cm pan evaporation outside, although pan evaporation outside is more consistent with ET_c than that inside. The value of α_{in}, calculated based on air temperature, relative humidity, and ground temperature inside, plays a dominant role in the calculation of ET_c. As the crop height increases, altering the location of the inside pan and placing it above the canopy, out of the shade, would help to achieve more reasonable values of crop evapotranspiration.

Key words: *crop evapotranspiration*; *pan evaporation*; *unheated greenhouse*; *tomato*; *cowpea*

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1 Introduction

Unheated greenhouses have been widely used in China for vegetable growth and production. Li (2005) has reported that there were 25 000 km^2 of protected vegetables cultivated in China from 2002 to 2003, and unheated greenhouses accounted for the majority. However, the development of reasonable irrigation hasn't proceeded at the same pace as the development of protected vegetable cultivation. The most popular irrigation method is still traditional furrow irrigation, which sustains a lot of water loss. Over-humidity caused by over-irrigation also results in plant diseases and pests. Optimal irrigation is quite essential to protected vegetable cultivation. Therefore, investigation into the water requirements of vegetables under greenhouse cultivation is urgent.

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Previous studies (Nimah et al. 1990; Yuan et al. 2001; Locascio and Smajstrla 1996) have illustrated the linear relationship between crop water requirements and pan evaporation both inside and outside greenhouses. Crop water requirements are often determined based on the pan evaporation (Castrignanò et al. 1990; Zhou and Sun 1997; Çetin et al. 2002; Blanco and Folegatti 2003). Experiments were carried out in an unheated greenhouse in Eastern China on tomato and cowpea crops, the most common types of vegetables cultivated in the area, in order to evaluate estimates of water requirements based on 20-cm pan evaporation inside and outside the greenhouse.

2 Materials and methods

Experiments were carried out on tomato (2001) and cowpea (2004) crops in an unheated greenhouse located in Chongchuan, Nantong of China (32°01'N, 120°56'E), which has a warm temperate monsoon climate with an average temperature of 15℃, and an average annual rainfall of 1 079.2 mm. The greenhouse had a metallic structure and was covered with a thick thermal-insulated polyethylene sheet, ventilated with opening side panels. The experiments were conducted in bottomed steel lysimeters with three replicates for each kind of crops. Lysimeters were surrounded by the same types of vegetables in the same density in order to avoid border effects. The size of the lysimeters was 55 cm×35 cm, with a soil depth of 60 cm inside. At the bottom of the lysimeters, beneath the soil, were coarse sand filter beds 20-cm in depth, and filter tubes used for drainage. Soil features, including bulk density, porosity, saturated moisture content, and field capacity of the top 0.5 m, are provided in Table 1. Vegetable features, including the variety, density, and dates of transplanting and harvesting, are provided in Table 2.

Table 1 Features of soil

Depth (m)	Bulk density (g/cm^3)	Porosity (%)	Saturated moisture content* (%)	Field capacity* (%)
0.1	1.244	53.1	42.7	30.4
0.2	1.369	48.3	35.3	25.8
0.3	1.486	43.9	29.6	24.8
0.4	1.492	43.7	29.3	25.0
0.5	1.441	45.6	31.7	25.8

*Calculated with gravimetric soil water content

Table 2 Features of vegetables

Name	Botanical name	Variety	Date of transplanting	Date of harvesting	Density
Tomato	*Lycopersicon esculentum*	Shanghaihezuo 908	2001-02-28	2001-06-30	2 plants per lysimeter
Cowpea	*Vigna unguiculata*	Yangjiang 40	2004-05-12	2004-07-20	4 plants per lysimeter

Single irrigation treatment, the most popular technique applied in unheated greenhouses in the Yangtze River Delta, was adopted. Irrigation in the lysimeters was synchronized to the irrigation outside the lysimeters in the same unheated greenhouse. Water was supplied to the lysimeters through drip irrigation when the record of tensiometers inside the lysimeters approached the record of tensiometers outside at the time of irrigation outside, and water volumes were recorded. Soil water potential in the root zone both inside and outside the lysimeters was monitored with tensiometers installed at 10-cm, 20-cm, and 30-cm depths. Lysimeters were weighed every five days with a TGT-500 balance (maximum 500 kg, the reduction of 50 g in weight equivalent to an ET_c of 0.3 mm in lysimeters), in order to determine the water consumption within the lysimeters. Actual evapotranspiration of the vegetable crops was computed using the water balance equation with the recorded weight:

$$ET_c = 10\frac{G_a - G_b}{A\rho} + I - D \tag{1}$$

where ET_c is crop evapotranspiration in mm; G_a and G_b denote the total weight of the lysimeter at the beginning and end of the period, respectively, in g; I and D denote the volume of irrigation and drainage in mm; ρ is the density of water, ρ=1.0 g/cm^3; A is the horizontal surface area of the lysimeters, A =1 925 cm^2.

Daily average temperature inside the greenhouse was recorded regularly with a thermometer, relative humidity was recorded with a wet and dry bulb, and pan evaporation was recorded with a 20-cm pan installed 70 cm above the soil surface. Outside the greenhouse, daily maximum and minimum temperatures were recorded regularly with a maximum and minimum thermometer, relative humidity was recorded with a wet and dry bulb, wind speed was recorded with an anemometer, pan evaporation was recorded with a 20-cm pan, and rainfall was recorded with a standard rain gauge.

The recommended fertilizer mixture (6750 g/m^2 of organic fertilizer, 75 g/m^2 of compost fertilizer, 75 g /m^2 of bean) and insecticide doses were applied to both tomato and cowpea crops. The crops were harvested from the lysimeters at the time of maturity, and the fresh yields of tomatoes and cowpeas were determined.

3 Results and discussion

3.1 Crop yield and crop water use efficiency

The seasonal total evapotranspiration, calculated by Eq. (1) based on the water balance, was 123.6 mm for tomatoes and 168.6 mm for cowpeas inside the greenhouse, with the appropriate value of total pan evaporation inside. These values are remarkably lower than those measured outside greenhouses in Northern China, 693.1 mm and 416.3 mm for tomatoes in Beijing and Tianjin, respectively (Chen et al. 1995), and 402.5 mm for cowpeas in Shanxi (Wang and Sun 2003). The evapotranspiration of tomatoes was a little lower than 153.5 mm recorded inside a greenhouse by Yuan et al. (2001). A remarkable reduction of vegetable crop evapotranspiration inside greenhouses has been reported in many cases. Seasonal total ET_c of greenhouse horticultural crops is quite low when compared with that of irrigated crops outside, such as sweet pepper (Beese et al. 1982), watermelon (Orgaz et al. 2005), melon (Fabeiro et al. 2002), and green bean (Barros and Hanks 1993; Hegde and Srinivas 1990; Orgaz et al. 2005). It can be concluded that greenhouses greatly reduce evapotranspiration by decreasing the radiation transmission coefficient and interrupting ventilation, thereby lowering evaporative demand. As shown in Table 3, pan evaporation inside the greenhouse ($E_{0\mathrm{in}}$) decreased remarkably as compared with that outside the greenhouse ($E_{0\mathrm{out}}$), even though the temperature inside the greenhouse increased (Table 3).

High yields, 8.91 kg/m^2 of tomatoes and 1.79 kg/m^2 of cowpeas, were attained in the protected, unheated greenhouse. High water use efficiency of evapotranspiration and irrigation ($\mathrm{WUE}_{\mathrm{ET}}$ and $\mathrm{WUE}_{\mathrm{IR}}$), 72.08 kg/m^3 and 76.28 kg/m^3 for tomatoes and 10.60 kg/m^3 and 12.51 kg/m^3 for cowpeas, respectively, were acquired (Table 3). Tomato yields were much higher than those reported by Mahajan and Singh (2006), both inside and outside the greenhouse. Higher yields in the greenhouse may be ascribed to the favorable environment. Environmental data taken inside the greenhouse (Table 4) revealed that the air temperature remained higher in the greenhouse than in the outside environment by an average of 0.95°C for tomatoes and 4.4°C for cowpeas, and that the relative humidity inside the greenhouse was higher than that outside by 11.1% for tomatoes and 14.6 % for cowpeas, respectively, which created a favorable microclimate for greenhouse crops. These results conform to those of Mahajan and Singh (2006).

Table 3 Crop evapotranspiration, fresh yield and water use efficiency

Crop	$E_{0\mathrm{out}}$ (mm)	$E_{0\mathrm{in}}$ (mm)	Evapotranspiration (mm)	Irrigation water (mm)	Fresh yield (kg/m^2)	$\mathrm{WUE}_{\mathrm{ET}}$ (kg/m^3)	$\mathrm{WUE}_{\mathrm{IR}}$ (kg/m^3)
Tomato	477.1	109.9	123.6	116.8	8.91	72.08	76.28
Cowpea	404.0	154.2	168.6	142.9	1.79	10.60	12.51

Table 4 Temperature and relative humidity inside and outside greenhouse during crop growing season

Month	Period	Tomato (2001)				Month	Period	Cowpea (2004)			
		T_{in}(℃)	T_{out}(℃)	Rh_{in}(%)	Rh_{out} (℃)			T_{in}(℃)	T_{out}(℃)	Rh_{in}(%)	Rh_{out}(%)
	F	14.4	7.7	94.6	65.0		F				
Mar.	S	14.6	10.5	87.9	73.6	May	S	27.5	20.6	90.9	73.8
	L	15.3	11.2	91.3	71.8		L	27.0	21.6	89.8	73.5
	F	16.4	13.4	93.7	80.4		F	27.6	22.2	86.0	65.3
Apr.	S	19.3	15.4	92.5	72.0	Jun.	S	28.2	24.5	87.1	80.4
	L	17.1	14.7	91.2	79.5		L	30.2	26.2	88.7	83.8
	F	19.7	17.9	96.0	82.8		F	30.6	27.0	90.9	80.6
May	S	25.5	22.8	85.7	70.6	Jul.	S	31.5	29.5	93.4	74.3
	L	24.7	22.0	81.7	74.7		L	27.5	20.6	90.9	73.8
	F	24.1	22.5	86.2	79.2						
Jun.	S	25.6	23.5	94.2	84.9						
	L	24.6	25.5	99.0	84.1						

Note: T_{in} and T_{out} mean temperature inside and outside the greenhouse, respectively; Rh_{in} and Rh_{out} mean relative humidity inside and outside the greenhouse, respectively. Throughout this paper, F, S and L refer to the first, second and last ten days of a month, respectively.

3.2 Temporal variation of crop evapotranspiration

Figure 1 shows the variation of measured ten-day cumulative evapotranspiration of tomato and cowpea crops with temperature and pan evaporation. For tomatoes, the ET_c increased with the development of the crop and reached a maximum of 18.4 mm in the middle of May when the plants' growth was most active. Then, the ET_c decreased in June when there were many rainy days. Analysis of the factors influencing tomato evapotranspiration shows that tomato ET_c varied in accordance with the increase of the temperature inside and 20-cm pan evaporation outside the greenhouse. For cowpeas, the ET_c also increased with the development of the crop, reaching a maximum of 33.6 mm at the end of the growing season in the middle of July. Analysis shows that the factors influencing cowpea evapotranspiration are similar to those affecting the evapotranspiration of tomatoes.

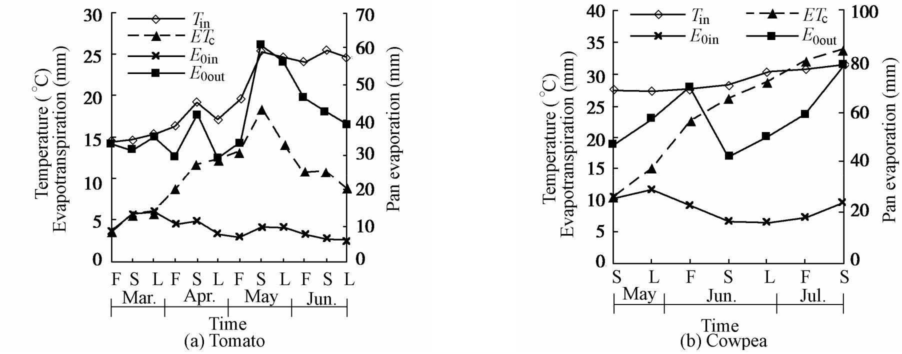

Figure 1 Evapotranspiration varying with temperature inside greenhouse and 20-cm pan evaporation both inside and outside greenhouse

However, the variations of cowpea and tomato ET_c were not in accordance with the variation of 20-cm pan evaporation inside the greenhouse, especially at later stages. This was attributed to the influence of shading when the vegetables were taller than the location where the pan was installed, 70 cm above ground. It is better to vertically move the pan in tandem with increasing crop height to ensure that it is located above the canopy and keep it out of the shade.

3.3 Ratios of crop evapotranspiration to pan evaporation

Ratios of crop evapotranspiration to pan evaporation are calculated as $\alpha= ET_c/E_0$, where E_0 is the pan evaporation. Figure 2 shows the variations of α_{in} and α_{out} for tomato and cowpea crops, which are the ratios calculated from 20-cm pan evaporation inside and outside the greenhouse, respectively. Unlike the linear relationship between evapotranspiration and pan evaporation noted by other researchers (Chartzoulakis and Drosos 1995; Nimah et al. 1990; Yuan et al. 2001), these results show that α_{in} and α_{out} varied from 0.4 to 2.0 and from 0.1 to 0.43 for tomato crops, and from 0.4 to 1.78 and 0.22 to 0.61 for cowpea crops, respectively. A similar variation of the crop coefficient K_c for horticultural crops was reported by Blanco and Folegatti (2003): K_c calculated by a pan inside varied from 0.16 to 1.44. Orgaz et al. (2005) also reported a similar variation of crop coefficient K_c, calculated with grass reference evapotranspiration inside the greenhouse: 0.2 to 1.4 for melon and bean, and 0.8 to 1.6 for cucumber. Results of α_{in} and α_{out} show the same variation throughout the growing season for tomatoes and cowpeas, but α_{in} variation lagged by about 20 days for tomato crops and 10 days for cowpea crops, with respect to the variation of α_{out}.

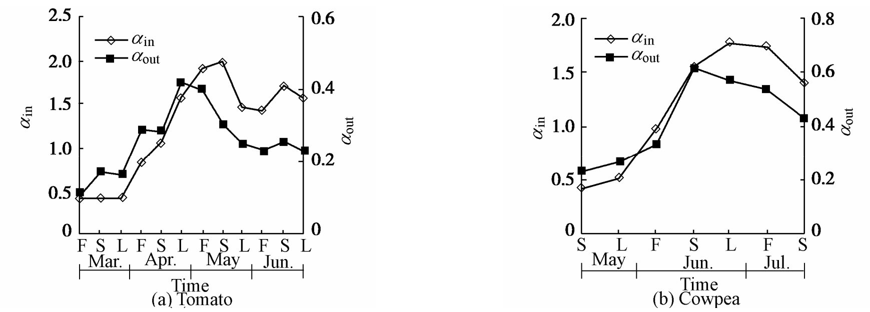

Figure 2 Ratio of crop evapotranspiration to 20-cm pan evaporation both inside and outside the greenhouse

3.4 Estimating crop evapotranspiration using pan evaporation

Since α_{in} and α_{out} varied greatly throughout the growing season, dynamic values of α_{in} and α_{out} were obtained from the analysis of the relations between the coefficient values and the environmental factors. For tomatoes, α_{in} was determined by the equation $\alpha_{in}= \beta T_A + \gamma Rh + \omega T_G + \delta$, where T_A was the air temperature, Rh was the relative humidity, T_G was the ground surface temperature inside the greenhouse, and β, γ, ω and δ were coefficients with the following values: $\beta = 0.317$, $\gamma = 0.037$, $\omega = -0.357$, and $\delta = -1.513$ (coefficient of determination $R^2 = 0.9062$, and significance level $p < 0.05$). The value of α_{out} was determined by the equation $\alpha_{out}= \beta \Delta T_A + \gamma \Delta Rh + \omega \Delta T_G + \delta$, where ΔT_A, ΔRh, and ΔT_G were the increase of air temperature, relative humidity and ground surface temperature inside the greenhouse as compared with those outside, respectively, and β, γ, ω and δ were coefficients with the following values: $\beta = 0.297$, $\gamma = 0.026$, $\omega = -0.349$, and $\delta = -0.218$ ($R^2 = 0.4838$, $p < 0.05$).

For cowpeas, α_{in} was simulated as $\alpha_{in}= \beta T_A + \gamma T_G + \delta$, where $\beta = 0.406$, $\gamma = -0.236$ and $\delta = -4.141$ ($R^2 = 0.9611$, $p < 0.05$), and α_{out} was simulated as $\alpha_{out}= \beta \Delta T_A + \gamma \Delta Rh + \omega \Delta T_G + \delta$, where $\beta = -0.002$, $\gamma = 0.015$, $\omega = -0.035$, and $\delta = -0.645$ ($R^2 = 0.9284$, $p < 0.05$).

Then, crop evapotranspiration was calculated as $ET_c = \alpha E_0$, and the values of α were calculated with the formulas presented above. Figure 3 and Figure 4 show crop evapotranspiration simulated with 20-cm pan evaporation both inside and outside the greenhouse.

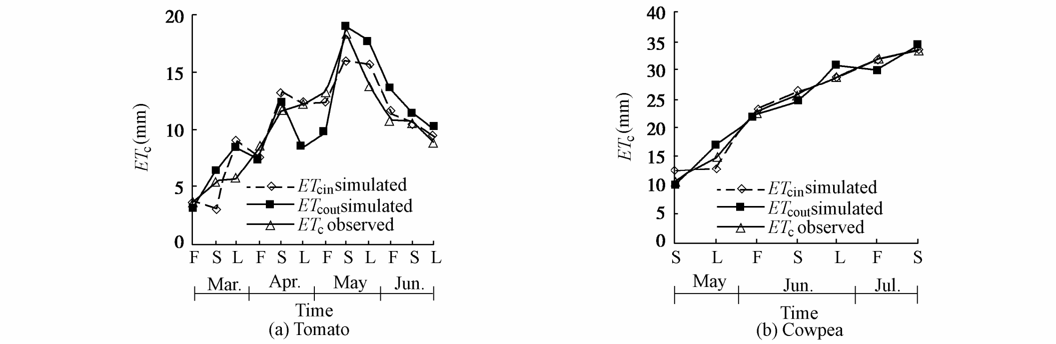

Figure 3 Simulated crop evapotranspiration ET_{cin} and ET_{cout} based on 20-cm pan evaporation inside and outside greenhouse

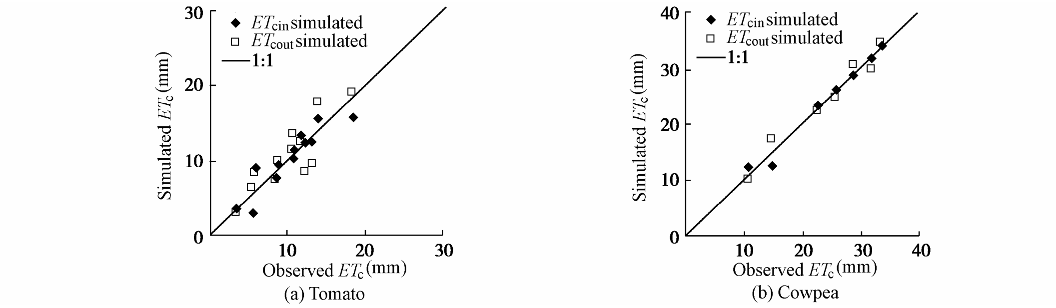

Figure 4 Comparison between observed and simulated crop evapotranspiration

Evapotranspiration derived from 20-cm pan evaporation inside the greenhouse performed much better than that from the outside, as has been reported in many case studies (Yuan et al. 2001; Blanco and Folegatti 2003). For tomatoes, simulation with inside pan evaporation had an average absolute error of 1.2 mm and a relative error of 14.88%, but simulation with the outside pan evaporation had an average absolute error of 1.84 mm and a relative error of 19.24%. For cowpeas, simulation with inside pan evaporation had an average absolute error of 0.80 mm and a relative error of 5.27%, but simulation with the outside pan evaporation had an average absolute error of 1.3 mm and a relative error of 6.26%.

Comparison of the simulated and observed values of crop evapotranspiration also illustrates the fact that simulation with inside pan evaporation performs well. For tomatoes, linear regression between the observed and simulated values yielded the equations ET_c=0.9229ET_{cin}+0.7476 ($R^2 = 0.8419$) and ET_c=0.7765ET_{cout}+2.0606 ($R^2 = 0.7442$), where ET_{cin} and ET_{cout} are the simulated values of evapotranspiration with the pan evaporation inside and outside the greenhouse, respectively. For cowpeas, linear regression between the observed and simulated values yielded the equations ET_c=0.9861ET_{cin}+0.3479 ($R^2 = 0.9802$) and ET_c=0.9902ET_{cout}+0.1933 ($R^2 = 0.9652$). It is more reasonable to determine tomato and cowpea crop evapotranspiration with 20-cm pan evaporation inside the greenhouse than with

20-cm pan evaporation outside. Without pan evaporation data inside the greenhouse, simulation with pan evaporation outside the greenhouse is also acceptable. As crops grow taller, moving the inside pan to keep it out of the shade would help to obtain more reasonable values of horticultural crop evapotranspiration.

4 Conclusions

Experiments carried out on tomato and cowpea crops in an unheated greenhouse in Eastern China show that evapotranspiration inside the greenhouse is remarkably lower than that outside. ET_c increases with the growth of the crop, and reaches its maximum at the stage when the plants' growth is most active.

Analysis of contributing factors shows that the value of 20-cm pan evaporation outside the greenhouse was more consistent with ET_c than that inside, because of the shade provided by crops when they were taller than the location where the inside pan was installed. Ratios of crop evapotranspiration to pan evaporation are not constant, as reported by other studies, and the variation of α_{in} lags behind the variation of α_{out}.

Simulation of crop evapotranspiration based on 20-cm pan evaporation inside the greenhouse is more reasonable than that based on the outside evaporation. The ratio α_{in} plays a dominant role in the calculation of ET_c, and it performs better than α_{out}. That is because α_{in} is calculated based on the air temperature, relative humidity, and ground surface temperature inside the greenhouse, and the air temperature inside is the parameter most consistent with the ET_c variation.

As the crop height increases, altering the location of the inside pan to ensure that it is located above the canopy and out of the shade of the plants will be helpful to obtaining more reasonable measurements of crop evapotranspiration.

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