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Response of evapotranspiration and yield to planting density of solar greenhouse grown tomato in northwest China

Rangjian Qiu[a,b,1], Jinjuan Song[a,1], Taisheng Du[a,*], Shaozhong Kang[a], Ling Tong[a], Renqiang Chen[a], Laosheng Wu[b]

[a] Center for Agricultural Water Research in China, China Agricultural University, Beijing 100083, China
[b] Department of Environmental Sciences, University of California, Riverside, CA 92521, USA

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ABSTRACT

Selecting proper planting density can optimize light interception and increase crop water productivity. This research investigated the planting density effect on the evapotranspiration (ET_c) and yield of greenhouse grown tomato in northwest China during December 2010 to June 2011 (first season), and September 2011 to January 2012 (second season). Five planting density treatments of 3.1, 3.7, 4.4, 5.0 and 5.6 plants m^{-2} were used and each treatment was replicated three times. The fifteen plots were randomized complete block design. The irrigation scheduling adopted was the same for all treatments and referred to a soil water depletion of 25 ± 2% below field capacity as observed for the 4.4 plants m^{-2} treatment. Water was applied beneath the plastic mulch covering both the bed and the furrow. The FAO 56 Penman–Monteith equation with a fixed aerodynamic resistance of 295 s m^{-1} was used to estimate the reference evapotranspiration (ET_0) in the greenhouse. The ET_c was calculated by the water balance method according to the change in soil water content over a period of time. The crop coefficients (K_c) at crop development stage in both growth seasons were calculated from ET_c/ET_0 and estimated by the equations proposed by Allen and Pereira (2009) that consider a plant density coefficient. Tomato yield and fruit number were also measured to assess the planting density effect on water productivity. Results showed that the seasonal total ET_c of the greenhouse grown tomato increased, while the seasonal total ET_c per plant decreased, linearly as planting density increased in both growth seasons. The calculated middle season K_c values from ET_c/ET_0 ranged from 0.77 to 0.83 in the first season and from 0.94 to 0.97 in the second season for different planting densities, which were lower than the K_c values estimated by Allen and Pereira's approach. Fruit number per plant, average single fruit weight and yield per plant decreased, but total yield increased, as planting density increased. From economical perspective, the recommended planting densities of tomato grown in northwest China's greenhouses are 3.7–4.4 plants m^{-2}.

1. Introduction

In recent years, tomato has quickly become one of the major vegetables grown in solar greenhouse in arid northwest China because of its high potential yield, water productivity and profitability. Selecting appropriate planting density to optimize light interception is one of the best management practices to increase tomato yield, because the productivity of tomato is strongly affected by the total solar radiation intercepted by the crop (Papadopoulos and Pararajasingham, 1997).

Generally, solar radiation intercepted by the crop increases with increasing planting density (Papadopoulos and Ormrod, 1988a). It is often observed that higher planting density has higher total yield, but many studies also show that flowering number, fruit set per plant and single fruit weight of tomato are lower when planting density is too high, which in turn results in lower yield of an individual plant (Agele et al., 1999; Amundson et al., 2012; Kirimi et al., 2012). Planting density effect on yield is also dependent on the seasons. Papadopoulos and Ormrod (1990) showed that the total and marketable yield of tomato increased linearly with planting density in fall, but they were highest at 4.0 and 3.1 plants m^{-2}, respectively, in spring.

The optimal planting density for tomato varies, depending on tomato varieties and environmental conditions. In open field, it is more efficient to grow a local late season tomato at 5.6 plants m^{-2} (60 cm × 30 cm) (Agele et al., 1999). In the greenhouse, the spacing of 50 cm × 30 cm for the 'Monkey Maker' tomato gave high

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* Corresponding author. Tel.: +86 10 62738548; fax: +86 10 62737611.
E-mail addresses: dutaisheng@cau.edu.cn, qiurangjian@gmail.com, dutaisheng@yahoo.com.cn (T. Du).

[1] Both authors contributed equally to this study.

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yields and it is easier to carry out cultural and agronomic practices efficiently (Kirimi et al., 2012). While an in-row spacing of 46 cm (consistent between-row spacing of 122 cm) was recommended for 'Trust' tomato growers wanting to maximize greenhouse space without negatively affecting yield or fruit weight (Amundson et al., 2012). In greenhouses of north China plain, Xu et al. (2009) concluded it is more economical to grow the tomato at 4.8 plants m^{-2}.

Microclimatic conditions can influence crop evapotranspiration (ET_c) (Liu, 2010; Yang et al., 1990; Zhang et al., 2010), and ET_c can also be affected by planting density (Allen et al., 1998). Higher planting density reduces radiation at the soil surface, but the increased radiant energy absorbed by plants can lead to accelerated rate of soil moisture depletion (Agele et al., 1999). The transpiration rate of greenhouse tomato plants increases at the closest spacing (23 cm spacing) due to the well exposed leaf area at the top of the plants (Papadopoulos, 1985; Papadopoulos and Ormrod, 1988b). Guttormsen (1974) also reported that greater planting density can result in a higher total evapotranspiration.

The 20 cm standard pan method (Liu et al., 2008), Priestley–Taylor method (Valdés-Gómez et al., 2009) and Penman–Monteith method (Montero et al., 2001; Medrano et al., 2005; Qiu et al., 2013; Stanghellini, 1987) are often used to estimate ET_c in greenhouses. But a simple and convenient method to estimate ET_c is to use 'crop coefficient (K_c) × reference evapotranspiration (ET_0)' (Allen et al., 1998; Doorenbos and Pruitt, 1975). The K_c value tends to decrease when plant density or leaf area is below the full ground cover condition. Allen and Pereira (2009) proposed to use a density coefficient (K_d) to describe the impact of plant density on K_c:

$$K_{cm} = K_{soil} + K_d \left[\max \left(K_{c\,full} - K_{soil}, \frac{K_{c\,full} - K_{soil}}{2} \right) \right] \quad (1)$$

where K_{cm} is the average K_c that considers the average impact of evaporation from soil. K_{soil} represents the average K_c from the non-vegetated (exposed) portion of the soil surface during the same period as K_d and $K_{c\,full}$, and $K_{c\,full}$ represents K_c from a fully covered soil with some background evaporation. When leaf area index (LAI) or fraction of ground cover (f_c) is measured or approximated, K_d can be estimated using the approaches by Allen et al. (1998):

$$K_d = (1 - e^{[-0.7LAI]}) \quad (2)$$

or by Allen and Pereira (2009):

$$K_d = \min(1,\ M_L f_{c\ eff},\ f_{c\ eff}^{1/(1+h)}) \quad (3)$$

where h is the average maximum crop height (m), $f_{c\,eff}$ is the effective fraction of ground covered or shaded by vegetation near solar noon. When the rows of plants run from north to south, $f_{c\,eff} \approx f_c$ since the soil is exposed to the sun at various times of the day, and the shaded area is the same as the fraction of vegetation cover at midday (Allen et al., 1998). The M_L parameter (a multiplier of 1.5–2.0) describes the effect of canopy density on shading and on maximum relative ET_c per fraction of ground shaded.

The parameter $K_{c\,full}$ in Eq. (2) can be approximated as a function of crop height and adjusted for climate (Allen et al., 1998; Allen and Pereira, 2009):

$$K_{c\ full} = \min(1.0 + 0.1h,\ 1.20) + [0.04(u_2 - 2) - 0.004(RH_{\min} - 45)]\left(\frac{h}{3}\right)^{0.3} + 0.05 \quad (4)$$

where u_2 is wind speed at 2.0 m height ($m\,s^{-1}$); $RH_{\min}$ is the average minimum daily relative humidity during the mid-season.

The FAO 56 Penman–Monteith method, recommended as the standard method for ET_0 estimation (Allen et al., 1998), calculates the aerodynamic resistance as a function of wind speed. The wind speed in solar greenhouse with natural ventilation is very low (0.01–0.2 $m\,s^{-1}$), which may result in much higher aerodynamic resistance values (20,800–1040 $s\,m^{-1}$). Fernández et al. (2010, 2011) reported that the FAO 56 Penman–Monteith equation with a fixed aerodynamic resistance of 295 $s\,m^{-1}$ can better estimate daily ET_0 in greenhouse:

$$ET_0 = \frac{0.408\Delta(R_n - G) + \gamma(628/(T + 273))(e_s - e_a)}{\Delta + 628\gamma} \quad (5)$$

where R_n is the net radiation ($MJ\,m^{-2}\,d^{-1}$), G is the soil heat flux ($MJ\,m^{-2}\,d^{-1}$), Δ is the slope of the saturated vapour pressure curve (kPa °C^{-1}), γ is the psychometric constant (kPa °C^{-1}), e_s is saturation vapour pressure (kPa), e_a is actual vapour pressure (kPa), $e_s - e_a$ (VPD) is the vapour pressure deficit (kPa). The calculation procedures of parameters R_n, G, e_s, e_a, γ, Δ and T were described in FAO 56 (Allen et al., 1998). Derivation of Eq. (5) with the selected aerodynamic resistance for the Penman–Monteith equation was described in Box 6 in FAO 56 (Allen et al., 1998).

In northwest China, planting density of greenhouse grown tomato is mainly based on farmer's experience, thus it is not always the same for each greenhouse. Only a limited number of studies have been conducted to test the effect of planting density on evapotranspiration of greenhouse grown tomato (Guttormsen, 1974; Papadopoulos and Ormrod, 1988b). To the best of our knowledge, no study has been conducted to investigate the effect of planting density on crop coefficient and water productivity of tomato in solar greenhouses under dry and cold climate conditions such as in northern China. Understanding the response of yield and water use to planting density and identifying the optimal planting density for tomato is of great importance for improving tomato yield, water productivity and farmers' profit. The objectives of this study were to (1) conduct experiment to evaluate the response of evapotranspiration and crop coefficient to tomato planting density in greenhouse condition; (2) assess the effect of planting density on K_d and consequently, on K_c, and (3) investigate the effects of planting density on yield and water productivity of greenhouse grown tomato.

2. Materials and methods

2.1. Experimental site and environmental conditions

Experiments were conducted in two consecutive years during December 2010 to June 2011 (first season), and September 2011 to January 2012 (second season) at the Wuwei Experimental Station of Crop Water Use, Ministry of Agriculture, Gansu Province, northwest China (N 37°52′, E 102°51′, altitude 1581 m). It is in a typical continental and temperate climate zone. The annual average temperature is 8.8 °C, the average annual frost-free period is 150 d, and the annual average precipitation is 164.4 mm. The groundwater table is below 25 m. Solar radiation is abundant in the region with annual average sunshine of 3000 h. Meteorological data outside and inside the greenhouse were measured by two automatic weather stations (Hobo, Onset Computer Corp., USA). The automatic weather station inside the greenhouse was located in the center of the greenhouse, and the outside one was 200 m away from the greenhouse. The measured meteorological data included rainfall (R), air speed at 2 m above ground (u_2) and wind direction, solar radiation (R_s), air temperature (T_a) and relative humidity (RH), but the R, u_2 and wind direction were not measured inside the greenhouse. The data were measured every 5 s, and 15 min averages were calculated and recorded using a data logger. During the first and second seasons, the average daily R_s was 190.0 and 124.8 $W\,m^{-2}$, the average daily T_a was 4.7 and −1.6 °C, the average daily RH was 47.3 and 56.1%, the average daily u_2 was 0.9 and 0.5 $m\,s^{-1}$, and the total R was 24 and 32 mm, respectively, outside the greenhouse. The average daily environmental condition at different growth stages

Table 1
Average daily environmental parameters at different growth stages of tomato inside the greenhouse. R_s is the solar radiation, T_a is the air temperature, *RH* is the relative humidity, *VPD* is the vapour pressure deficit, and ET_0 is the reference evapotranspiration.

Season	Growth stage	R_s (W m^{-2})	T_a (°C)	*RH* (%)	*VPD* (kPa)	ET_0 (mm d^{-1})
2010–2011	Initial (December 26, 2010–January 30, 2011)	65.4	12.3	75.0	0.58	1.55
	Development (January 31–March 15)	98.8	17.9	79.3	0.71	2.22
	Middle (March 16–May 26)	175.3	21.9	78.6	1.00	3.88
	Late (May 27–June 26, 2011)	192.2	23.9	66.8	1.49	4.44
	Entire season	138.5	19.4	76.1	0.93	3.13
2011–2012	Initial (September 21, 2011–October 20)	112.5	18.9	70.3	1.04	2.60
	Development (October 21–November 30)	84.9	16.3	84.9	0.46	1.62
	Middle (December 1–January 21, 2012)	73.4	15.0	87.6	0.37	1.32
	Late (January 22–February 19, 2012)	82.7	15.4	84.6	0.48	1.90
	Entire season	86.7	16.1	82.5	0.56	1.76

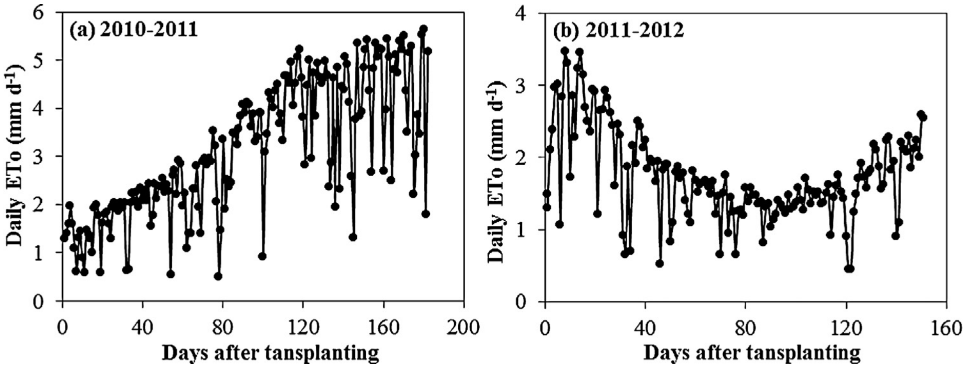

Fig. 1. The seasonal variation of daily reference evapotranspiration (ET_0) calculated using Eq. (5) in the first (a) and second season (b).

of tomato inside the greenhouse is shown in Table 1, and the seasonal variation of daily ET_0 calculated using Eq. (5) is shown in Fig. 1. The planting dates and the lengths of the two growth seasons were different (Table 1), correspondingly, the environmental conditions were different for the two growth seasons. The seasonal daily averages of R_s, T_a and ET_0 were 37, 17 and 56% lower in the second season than those in the first season; while the daily averages of *RH* was 8% higher in the second season than in the first season.

The solar greenhouse was made of a steel frame, 76 m long × 8 m wide, covered with a 0.2 mm thick thermal polyethylene sheet. Because the greenhouse had no heating system, straw mats were spread over the greenhouse roof surface of the thermal polyethylene sheet during December to May in the first season, and during November to February in the second season to maintain the interior temperature at night. The greenhouse interior temperature during the daytime was controlled by a narrow ventilation system on the roof with the maximum opening of 50 cm. More details of the solar greenhouse construction were described by Qiu et al. (2011). The soil is a desert sandy loam (Siltigic–Orthic Anthrosols) with an average bulk density of 1.46 g cm^{-3}, field water capacity (θ_{FC}, water content at −33 kPa) of 0.36 (cm^3 cm^{-3}) and wilting point (θ_{WP}, water content at −1.5 MPa) of 0.10 (cm^3 cm^{-3}). The electrical conductivity of irrigation water was 0.52 dS m^{-1}.

2.2. Experiment design

The experiment had five planting density treatments of 3.1, 3.7, 4.4, 5.0 and 5.6 plants m^{-2}, which are referred as D_1, D_2, D_3, D_4, and D_5. Different planting densities in the experiment were achieved by different plant spacing in the row, i.e., 56, 47, 40, 35 and 31 cm, respectively, for D_1, D_2, D_3, D_4, and D_5. There were three replications per treatment resulting in a total of 15 plots arranged in a randomized complete block design. The area of each plot, including two furrows and two beds, was 12.9 m^2 (5.6 m long × 2.3 m wide). The widths of the furrow and adjacent bed were 40 and 75 cm, respectively (Fig. 2).

In order to keep the seedlings alive and to enhance growth, two irrigation events with the same water amount, 16.0 and 18.6 mm, respectively, were applied at transplanting and 10–15 days after transplantation (DAT) for the first and second seasons. From 10–15 DAT, tomato crops were irrigated to 90% of the field capacity (θ_{FC}) when average soil water content in the main root zone (Z_r = 50 cm) for the 4.4 plants m^{-2} was depleted to 75 ± 2% of θ_{FC}. For each irrigation, the amount of water applied, *D* (mm), was calculated as follows:

$$D = 10 \times (0.9\theta_{FC} - \theta_i) \times Z_r \quad (6)$$

where θ_i is the average initial soil water content of D_3 before irrigation (cm^3 cm^{-3}). Soil water content was measured using a portable capacitance sensor system (Diviner 2000, Sentek Pty Ltd., Australia). Calibration of the Diviner 2000 was conducted at the experimental site by determining the water contents of soil samples using gravimetric method as near as possible to the probe in both growth seasons. Two PVC access tubes (1.0 m in length and 0.05 m internal diameter) were installed in each plot with one on the center of bed, and the other in the middle furrow (Fig. 2). Every 7–10 days measurements were made at 0.1 m intervals with maximal soil depth of 1.0 m.

The amount and time of irrigation were the same for all treatments in each of the growth seasons (Table 2). Water was applied

Table 2
Irrigation amount (mm) and frequency of greenhouse grown tomato at different growth stages in both growth seasons. The numbers in the brackets indicate total irrigation times for the respective growth stage. The irrigation amount and time were the same for all treatments in each of the seasons.

Season	Initial	Development	Middle	Late	Entire
2010–2011	32.0 (2)	55.9 (2)	223.6 (8)	83.9 (3)	395.4 (15)
2011–2012	37.3 (2)	55.9 (2)	55.9 (2)	27.9 (1)	177.0 (7)

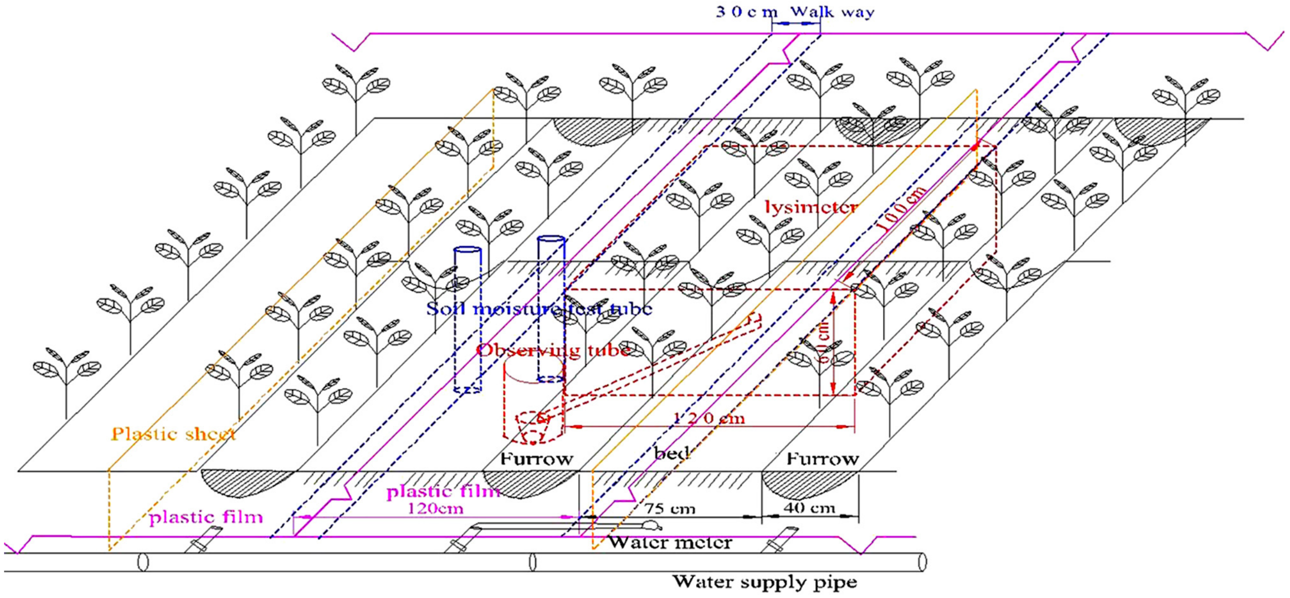

Fig. 2. Planting pattern of tomato and arrangement of soil moisture access tubes, lysimeter and walkway.

to the dead end furrow side and no tail flow was allowed, and the amount of irrigation was recorded for each plot by a water meter (accuracy of 0.1 L) at the end of the pipe. In order to prevent lateral movement of soil water to neighboring plots, a plastic sheet was embedded in the soil to a depth of 0.6 m around each plot.

2.3. *Crop management*

During the first season, the tomato (*Solanum lycopersicum L.*, cultivar *Zhongyan*) plants were transplanted on December 26, 2010. In the second season, the tomato plants (*S. lycopersicum L.*, cultivar *O yadi*) were transplanted on September 21, 2011. These two tomato varieties were the local leading varieties and belong to pink tomato series. The different dates of transplanting for the two growth seasons represent the typical annual rotation of the crops grown in solar greenhouses in the region. The crop grown before the first season was green beans. The crop after the second season was tomato, transplanted on February 28, 2012. The lengths of the four crop growth stages in each season were divided as proposed by Allen et al. (1998) (Table 1).

Two rows of seedlings were evenly transplanted along the edge of each furrow. The plant rows were oriented in a north–south direction for better interception of sunlight. At 3–10 DAT, the entire soil surface was covered with clear, 0.005 mm thick polyethylene film to reduce soil evaporation and to increase soil temperature. At 30–40 DAT, the stems were hung with plastic string to a trellis system, and the flowers were manually treated using p-chlorophenoxy acetic acid solution in all plots.

During the first season, harvesting started on March 26 and ended on June 26, 2011. Branch stems were pruned on March 21, April 8, 28 and May 24, 2011. During the second season, harvesting started on December 26, 2011 and ended on February 19, 2012. Branch stems were pruned on November 28, 2011. Throughout each growth season, other agronomic management practices such as pollination, pruning branch stem, fertilization and pest control were the same for all treatments.

2.4. *Measurements and methods*

2.4.1. *Leaf area index and fraction of ground cover*

From 5 DAT, leaf area index (*LAI*) was measured using a nondestructive SunScan canopy analysis system (Delta-T Devices Ltd., England) every 5–20 days, as well as before and after pruning events.

Fraction of ground cover (f_c) for the five planting densities as a function of time was estimated assuming that the initial radius of the seedlings was 2 cm and that the radius increased linearly with time, resulting in plants touching for D_3 in 50 days, based on the photos taken during the experiment. Considering the effect of walkway which was always 30 cm width in the bed (Fig. 2), the maximum f_c was 0.74 in this research.

2.4.2. *Soil water balance*

Crop evapotranspiration was calculated using the water balance method by monitoring the change in soil water content over a period of time (Allen et al., 2011). There was no precipitation in the greenhouse and no surface runoff from the plots since all furrows were blocked. Contribution from groundwater table was also negligible since the water table was below 25 m. Non-weighting, percolation type lysimeters (1 mm thick steel) of 1.0 m long and 1.2 m wide were installed 0.6 m beneath the bottom of the furrow (Fig. 2) to collect drainage water. However, no drainage was observed from the lysimeters in each of the plots. Thus ET_c (mm) can be estimated by:

$$ET_c = I - \Delta S \tag{7}$$

where I is irrigation (mm) and ΔS is the change in soil water storage in the root zone (mm).

2.4.3. *Yield and water productivity*

Ripe tomatoes were harvest and fresh total yield (Y) and total number (N) of tomatoes from all plants at each plot were measured at each harvesting. Fruit size of individual harvested tomatoes was not measured. The water productivity (WP, kg m^{-3}) was calculated using the following equation:

$$WP = \frac{Y}{ET_c} \times 1000 \tag{8}$$

where Y is total fruit yield (kg m^{-2}).

Table 3
The total evapotranspiration (ET_c) (mm) at different growth stages and the seasonal ET_c per plant (kg plant^{-1}) of greenhouse grown tomato under different planting densities. Means within columns followed by different letters (a–e) are significantly different at $P_{0.05}$ level.

Season	Treatment	Initial	Development	Middle	Late	Entire	ET_c per plant
2010–2011	D_1	29.1	52.0	215.5	108.1	404.8d	130.2a
	D_2	31.8	52.3	227.0	101.4	412.5c	110.6b
	D_3	33.7	58.5	231.2	101.0	424.3b	97.6c
	D_4	34.5	61.9	227.1	103.6	427.1b	86.0d
	D_5	35.0	64.5	232.2	104.8	436.5a	78.1e
2011–2012	D_1	38.6	43.0	66.2	27.5	175.3d	56.5a
	D_2	38.7	50.2	65.3	29.1	183.3c	49.2b
	D_3	45.5	47.6	65.0	28.5	186.6bc	42.9c
	D_4	45.9	48.2	67.1	27.5	188.7b	38.0d
	D_5	47.3	51.6	65.1	30.7	194.7a	34.7e

2.5. Statistical analysis

Analysis of variance (one-way ANOVA) and the mean separations (Duncan's multiple range tests at significant level of 0.05) were performed by SPSS 13.0 version software (SPSS Inc., USA).

3. Results

3.1. Planting density effect on evapotranspiration and crop coefficient

The daily average ET_c calculated for each of the 7 to 15-day intervals increased linearly as R_s ($ET_c = 0.24R_s - 0.53$, $R^2 = 0.88$), T_a ($ET_c = 0.24\,T_a - 2.43$, $R^2 = 0.76$), and VPD ($ET_c = 2.19$ VPD + 0.21, $R^2 = 0.56$) increased based on the pooled data from all treatments. The daily average ET_c was significantly influenced by R_s, T_a and VPD ($P < 0.001$), and the correlation between the daily average ET_c and R_s was higher than those for T_a and VPD. Similar relationships between the daily average ET_c and R_s, T_a and VPD were observed under different planting densities.

Due to the differences in planting time, length of the growth season, and microclimate conditions, the total seasonal ET_c for the first season was about twice that of the second season for all planting density treatments (Table 3). The total ET_c for the entire season increased, while the total ET_c per plant decreased, linearly with the increase of planting density (Table 3). The differences in ET_c among planting density treatments occurred mainly at the first two growth stages in both growth seasons as well as the middle stage in the first season.

The calculated tomato crop coefficients (K_c) from ET_c/ET_0 were similar for both seasons based on their respective seasonal total ET_c and ET_0 values. At different growth stages for different planting densities, the K_c values varied from 0.53 to 0.83 in the first season and from 0.51 to 0.97 in the second season (Table 4). Comparison between the K_c values estimated from Allen and Pereira's equations and those calculated from ET_c/ET_0 at the crop development stage in both growth seasons is shown in Fig. 3. Due to the plastic film mulch, we assumed that K_{soil} is 0.10 in Allen and Pereira's equations, which is lower than the value of 0.15 used by them (Allen and Pereira, 2009). During the mid-season the average maximum plant heights were 1.8 and 1.6 m, and the average RH_{min} values were 37.2 and 56%, respectively, for the first and second season. The K_c values estimated from Allen and Pereira's equations that consider the density coefficient (K_d) with LAI or f_c were higher than those calculated from ET_c/ET_0 (Fig. 3). The slope of the regression between the estimated K_c values from Allen and Pereira's equations with K_d (LAI) or K_d (f_c) and those calculated from ET_c/ET_0 was 1.39 and 1.28, respectively, and they have a correlation ($P < 0.001$) with R^2 of 0.46 and 0.82, respectively. The K_c values estimated from Allen and Pereira's equations with K_d (f_c) were closer to the K_c values calculated from ET_c/ET_0. Comparison of the K_c values other than the crop development stage was not done because the differences in K_c among the treatments were small in the initial stage, middle and late stages among all planting densities.

Table 4
The crop coefficients (K_c) calculated from ET_c/ET_0 at different growth stages of greenhouse grown tomato under different planting densities.

Season	Treatment	Initial	Development	Middle	Late	Entire
2010–2011	D_1	0.54	0.53	0.77	0.79	0.71
	D_2	0.59	0.53	0.81	0.74	0.72
	D_3	0.62	0.60	0.83	0.73	0.75
	D_4	0.64	0.63	0.81	0.75	0.75
	D_5	0.65	0.66	0.83	0.76	0.77
2011–2012	D_1	0.51	0.65	0.96	0.50	0.66
	D_2	0.51	0.76	0.95	0.53	0.69
	D_3	0.60	0.72	0.94	0.52	0.70
	D_4	0.61	0.73	0.97	0.50	0.71
	D_5	0.63	0.78	0.94	0.56	0.73

3.2. Response of yield and water productivity to planting density

Fig. 4 shows that the fruit number per plant and the average single fruit weight declined linearly as planting density increased. The yield per plant of ripe tomato also decreased significantly as planting density increased in both growth seasons (Table 5). However, the total yield of ripe tomato increased rapidly as planting density increased until it reached 4.4 plants m^{-2}, while there was only a small increase in the total yield when planting density was greater than 4.4 plants m^{-2}. Significantly ($P < 0.05$) lower yield was only observed at D_1 (Table 5), where the total yield was 9.4 and 11.8%, respectively, lower than those of D_5 for the two growth seasons.

The water productivity values (WP) ranged from 40.8 to 43.1 kg m^{-3} in the first season and from 55.7 to 58.2 kg m^{-3} in the second season under different planting densities (Table 5). Except for D_1 in the first season, the impact of planting density treatment on WP was not significant ($P > 0.05$). The trends in WP as affected by planting density were similar for both seasons. For the first season, WP values for D_2 and D_3 were higher than those for other treatments, which is similar to what occurred in the second season. Compared to the first season, WP in the second season was higher due to lower ET_c in the second season.

4. Discussion and conclusions

In this study, the daily average ET_c of greenhouse grown tomato calculated for each of the 7 to 15-day intervals increased linearly as R_s, T_a and VPD increased. The results were consistent with the study by Liu (2010), but the correlation between the daily average ET_c and the meteorological variables in their study was relatively lower than that in this study. Similar results were also reported in greenhouse grown cucumber (Yang et al., 1990; Zhang et al., 2010).

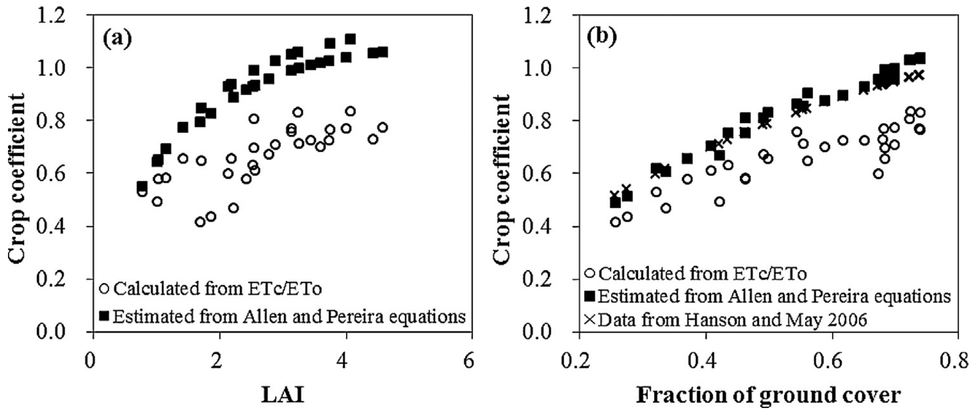

Fig. 3. The K_c versus *LAI* (a) and f_c (b) for greenhouse grown tomato with calculated K_c from ET_c/ET_0 and estimated by Eqs. (1–4) at the crop development stage in both growth seasons. The symbols '×' in (b) represent the data calculated from the regression equation by Hanson and May (2006).

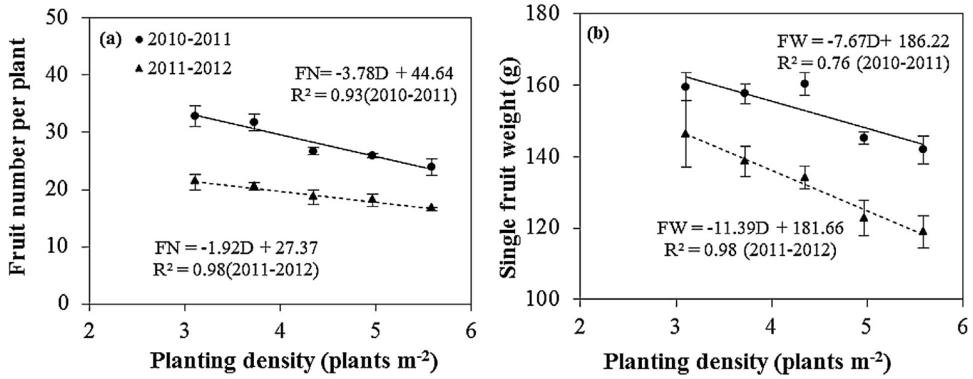

Fig. 4. Relationship between fruit number per plant (a), average single fruit weight (b) and planting density. *FN* is fruit number per plant, *FW* is single fruit weight and *D* is planting density. Vertical bars represent ±S.D. of measurements in each treatment.

The differences in ET_c among planting density treatments can be attributed to their differences in leaf area index (*LAI*). Higher planting density resulted in larger *LAI* (Fig. 5), which in turn increased canopy interception of radiation energy, leading to increased ET_c. But when *LAI* reached a threshold value, the energy intercepted by the canopy did not increase greatly with the further increase of *LAI*. Under such circumstance greater leaf area will not significantly affect ET_c.

The range of the calculated K_c values from ET_c/ET_0 for both growth seasons was different in this study. Wide range of tomato K_c values was reported in the literature. In an open filed, Pruitt et al. (1972) showed that the K_c values of processing tomato under sprinkler irrigation was 0.22 at the initial stage, 1.25 at the mid-season stage and 0.60 at the late season stage. Doorenbos and Pruitt (1975) reported that the tomato K_c values ranging from 1.2 for wind speeds of 0–5 m s^{-1} and 1.25 for speeds of 5–8 m s^{-1} in the mid-season. A maximum average crop coefficient of 1.05 was found in a lysimeter experiment at a site along the west side of the San Joaquin Valley (Phene et al., 1985). Snyder et al. (1987) reported that the tomato K_c values ranged from 0.2 to 0.26, 1.0 to 1.2 and 0.3 to 0.9, respectively, in the initial, middle and late season in different parts of USA. Allen et al. (1998) showed that the tomato K_c values were 0.6, 1.15 and 0.7–0.9, respectively, in the initial, middle and late stage. Hanson and May (2006) showed that the average mid-season K_c varied from year-to-year (2001–2004) with values ranging from 0.96 to 1.09. In a greenhouse, Abedi-Koupai et al. (2011) also reported that the tomato K_c in the initial, development, middle and late season was 0.44, 0.68, 1.15 and 0.68, respectively.

The calculated K_c values from ET_c/ET_0 at the crop development stage for both growth seasons in this study were considerably lower

Table 5
Yield and water productivity (*WP*) of greenhouse grown tomato under different planting densities. Means within columns followed by different letters (a–e) are significantly different at $P_{0.05}$ level.

Growth season	Treatment	Total yield (kg m^{-2})	Yield per plant (kg plant^{-1})	ET_c (mm)	*WP* (kg m^{-3})
2010–2011	D_1	16.5b	5.3a	404.8	40.8b
	D_2	17.7a	4.8b	412.5	43.0a
	D_3	18.3a	4.2c	424.3	43.2a
	D_4	17.8a	3.6d	427.1	41.6a
	D_5	18.2a	3.3e	436.5	41.7a
2011–2012	D_1	9.7b	3.1a	175.3	55.1a
	D_2	10.6a	2.8b	183.3	57.9a
	D_3	10.9a	2.5c	186.6	58.5a
	D_4	11.0a	2.2d	188.7	58.3a
	D_5	11.0a	2.0e	194.7	56.5a

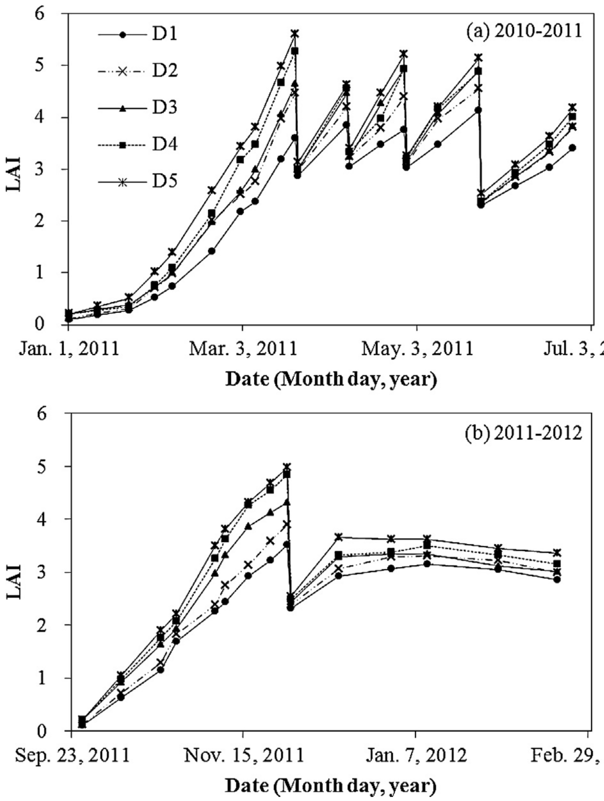

Fig. 5. Evolution of *LAI* through the entire growth season in different planting densities.

than the values reported in the literature, both in open field (Allen et al., 1998; Phene et al., 1985; Pruitt et al., 1972; Snyder et al., 1987) and in greenhouse (Abedi-Koupai et al., 2011), which are attributed to the following reasons: (1) higher humidity and lower air speed in the greenhouse were observed at this growth stage in greenhouse. More humid climate and lower air speed can result in lower K_c values (Allen et al., 1998); (2) there was no crop transpiration from plastic mulched walkway areas, which lowered the K_c; (3) plastic mulch can reduce K_c by 10–35% in the middle growth stage (Allen et al., 1998; Amayreh and Al-Abed, 2005; Haddadin and Ghawi, 1983); and (4) the calculate ET_0 with FAO 56 Penman–Monteith equation with a fixed aerodynamic resistance of 295 s m^{-1} may somewhat contribute to the difference. The ET_0 equation worked well in the Mediterranean climate, but it may require adjustment of the aerodynamic resistance for greenhouses in arid region of northwest China. This was partially evidenced in the relationship between K_c values estimated from Allen and Pereira's equations and those calculated from ET_c/ET_0: the K_c values estimated from Allen and Pereira's equations with K_d (f_c) in this study were similar to those in Hanson and May (2006) (Fig. 3b), but higher than those calculated from ET_c/ET_0. It means that the aerodynamic resistance in greenhouses in northwest China may be higher than 295 s m^{-1}, which in turn overestimated the ET_0.

The yield per plant of greenhouse grown tomato decreased significantly as planting density increased in both growth seasons (Table 5), and higher planting density had an adverse effect on fruit number per plant (Fig. 4(a)) and average single fruit weight (Fig. 4(b)). Similar results were also found by Frost and Kretchman (1988) and Kirimi et al. (2012). The total yield of ripe tomato increased rapidly as planting density increased until it reached 4.4 plants m^{-2} from which there was only a small increase in the total yield with the increase of planting density (Table 5). Plant biomass production is directly related to radiation interception (Loomis and Connor, 1992). The proportion of available radiation interception is higher because of higher *LAI* under higher planting density (Fig. 5), which results in higher canopy photosynthesis and biomass production and increase in the proportion of dry matter allocated to fruits. But further increase in *LAI* above certain threshold will not increase radiation interception greatly (Loomis and Connor, 1992). This might explain why increase in planting density above a threshold value will not further increase yield.

Table 5 shows that significant ($P < 0.05$) decrease of the total yield was only observed at D_1. Thus is not recommended to grow tomato at density lower than 3.1 plant m^{-2}. However, the total yield did not increase significantly and single fruit weight became lower when planting density was too high. When planting density is too high, it also becomes more difficult in carrying out cultural and agronomic practices efficiently. Therefore it is more economical to grow tomato at planting density of 3.7–4.4 plants m^{-2} in greenhouses in northwest China.

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