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Crop coefficient and water-use efficiency of winter wheat/spring maize strip intercropping

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ABSTRACT

Winter wheat and spring maize strip intercropping system is widely practiced in northern China. In this study, a field experiment with typical winter wheat and spring maize strip intercropping systems was carried out in 2003–2004 and 2004–2005 seasons to investigate crop coefficient (K_c, defined as the ratio of actual crop evapotranspiration to reference crop evapotranspiration) and water-use efficiency (WUE, defined as the ratio of grain yield to total actual evapotranspiration) of intercropping systems in the Huang-Huai-Hai Plain of China.

Crop coefficient values of sole winter wheat varied in ranges of 0.26–0.36, 1.09–1.15 and 0.27–0.41 at initial, mid and late season in two seasons, respectively. K_c values of sole spring maize varied in 0.36–0.37, 1.18–1.19 and 0.22–0.28 at initial, mid and late season in two seasons, respectively. K_c values of winter wheat/spring maize intercropping system varied in 0.31–0.35, 1.14–1.23 at initial and middle wheat growing season, in 0.65–0.70 at wheat-maize co-growing period, and in 1.24–1.25 and 0.21–0.27 at middle and late maize growing season in two seasons, respectively.

Compared to yields of spring maize and winter wheat in monoculture, total grain yield (wheat + maize) of winter wheat/spring maize intercropping system increased by 39% and 98%, respectively. Average WUE in the intercropping system was 21.72 kg ha^{-1} mm^{-1}, which was 23% less than that of the sole maize, but 4% greater than that of the sole wheat (4%). Therefore, although winter wheat/spring maize intercropping system does not improve WUE, it may significantly raise yield, which is helpful to ensure food safety in northern China.

1. Introduction

Intercropping, namely culturing two or more crops together on same field and at same time, is an intensive management for crop production both in time and in space (Xin and Tong, 1986). In China, one-third of the cultivated lands is used with intercropping systems and is supplying about half of the total grain products (Zhang and Li, 2003). It can be said that intercropping has been playing a very important role in ensuring grain supply and improving farmers' income in China (Zhang et al., 2007b).

Huang-Huai-Hai Plain is one of the most important grain production regions in China. Wheat and maize are two main grain crops, and cultivated area and grain products hold about 36% and 37% of the national total values, respectively. However, The Plain holds only 7.2% of national total available water resources, which is a main factor of restricting seriously regional agricultural production (CNBS, 2006; Zhang et al., 2007a). Therefore, it is imperative to improve water and land-use efficiency for sustainable development of grain production in the Plain.

Under intercropping systems, agricultural resources, i.e., land, nutrient, water, heat and radiation resources may be utilized more effectively both in time and in space (Rodrigo et al., 2001; Willey, 1990). Many studies indicated that higher radiation-use efficiency (Awal et al., 2006; Tsubo et al., 2001), nutrient-use efficiency (Benites et al., 1993; Li et al., 2001; Rowe et al., 2005), water-use efficiency (Mandal et al., 1996; Morris and Garrity, 1993; Reddy and Willey, 1981; Walker and Ogindo, 2003), and land-use efficiency (Dhima et al., 2007; Zhang et al., 2007b) may be achieved with intercropping. Compared to monoculture, a higher yield has been recorded in many intercropping systems, including

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maize/bean (Tsubo and Walker, 2002), wheat/maize (Li et al., 2001), wheat/chickpea (Mandal et al., 1996), maize/peanut (Awal et al., 2006), and wheat/cotton (Zhang et al., 2007b), and so on. Wheat/maize strip intercropping, a common intercropping system in northern China, may improve yield by 40–70% (Li et al., 2001; Cao et al., 2006).

There are two kinds of typical strips in winter wheat/spring maize strip intercropping. One is wheat strip, which consists of a few rows of wheat plants sown in fall with normal raw space, and another is spring maize strip, which is bare during early wheat season and planted with maize in late wheat season in spring. The two kinds of strip are ranged one by another in field and the co-growing period of the two crops is about 50 days in the intercropping system. In Huang-Huai-Hai Plain, 60–80% of annual rainfall occurred during June to August, which covers most of the maize season, but rainfall was scarce during co-growing period of two crops, which usually become the major factor of restricting high yield. Therefore, estimating crop evapotranspiration (ET_c) and determining irrigation water requirement accurately are necessary for optimal irrigation schedule to ensure yield stability of the intercropping system.

Crop coefficient (K_c) is a very important item for evaluating crop evapotranspiration (Allen et al., 1998; De Medeiros et al., 2001, 2005; Er-Raki et al., 2007; Williams and Ayars, 2005) and is defined as the ratio of actual crop evapotranspiration (ET_c) to reference crop evapotranspiration (ET_0) (Allen et al., 1998; Doorenbos and Kassam, 1979). Here ET_0 is usually estimated with Penman-Monteith equation recommended by FAO (Allen et al., 1998), and ET_c is commonly measured with lysimeters installed in field (Benli et al., 2006; Miranda et al., 2006; Williams and Ayars, 2005) or with water balance method in case without lysimeter facilities (Azizi-Zohan et al., 2008; Kar et al., 2007). Crop coefficient varies significantly in whole crop growing season. K_c increases in early season as canopy's coverage increase, maintains at a plateau for some time during period of canopy's largest coverage to soil, and then decreases as crop senesces. FAO papers presented values of crop coefficient for a large number of crops in monoculture (Allen et al., 1998; Doorenbos and Kassam, 1979). Crop coefficients of wheat and maize in monoculture have been investigated in Huang-Huai-Hai Plain of China (Duan et al., 2004; Teixeira et al., 1996). However, few researches and results about K_c of intercropping system have been documented. For wheat/maize strip intercropping systems, canopies are not homogeneous and crop coefficients are different from that for monoculture.

Comparisons were made by contrasting data from intercropping (such as maize/cowpea, mustard/chickpea, maize/mung bean, sorghum/cowpea, pigeon pea/sorghum intercropping systems, etc.) against weighted means from ones of relevant crops in monoculture with proportions of soil area occupied by each sole crop in intercropping system as weighted-mean coefficients. Morris and Garrity (1993) indicated that water-use efficiency (WUE) of intercropping system are usually greater than the WUE of monoculture by 4–99%, and over 18% in many cases. But there were also some exceptions. Cowpea/pear millet and cowpea/sorghum intercropping systems did not increase obviously WUE (Grema and Hess, 1994; Shackel and Hall, 1984), or sometime reduced WUE (Rees, 1986a,b; Singh et al., 1988). In intercropping systems mentioned above, the co-growing period exceeds almost half of the whole growth season. However, co-growing period is only about 15% of the whole growth season in the winter wheat/spring maize intercropping system, and few studies are conducted to investigate crop coefficient and WUE of the system. The objectives of this study are to investigate crop coefficient and WUE of the winter wheat/spring maize intercropping system by field experiments, and to improve water management of the system.

2. Materials and methods

2.1. Experimental site description

Field experiments for winter wheat/spring maize intercropping were conducted over two growing seasons (2003–2004 and 2004–2005) at experimental station of Farmland Irrigation Research Institute (35°19′N, 113°53′E, 73.2 m), located in Xinxiang City of Henan Province, in the Huang-Huai-Hai Plain. On averages of 50-year weather data taken from Xinxiang Weather Station very near the experimental field, the annual mean air temperature is 13.5 °C, annual accumulated temperature above 0 °C is 5070.2 °C, annual sunshine duration 2497 h, frost-free period 220 days, precipitation 580 mm and potential evaporation (measured with 20 cm pan) 2000 mm. Groundwater table is over 8 m. Soil is sandy loam with mean bulk density of 1.35 g cm^{-3}, mean field capacity of 24% (gravitational content) and mean permanent wilting point of 8% (gravitational content) in 0–100 cm profile. Soil available N, P and K contents were 72, 17.8 and 100 mg kg^{-1}, respectively, and soil organic matter content was 10.3 g kg^{-1} at before first winter wheat growing season.

2.2. Experimental design

The field experiments were designed and settled by random complete block method with three treatments and three replications. Three treatments were: sole winter wheat, sole spring maize and winter wheat/spring maize strip intercropping. In strip intercropping system, each wheat strip consists of four rows of wheat plants and each maize strip of two rows of maize plants, which are widely practiced locally. Row space was 15 and 55 cm for sole wheat and sole maize treatment, respectively. In strip intercropping treatment, inter-row space was 15 cm for wheat and 50 cm for maize, the distance between wheat strip and maize strip was 15 cm (see Fig. 1).

Selected winter wheat and spring maize cultivars were 'Bainong 66' and 'Nongda 108', respectively. Seeds were placed

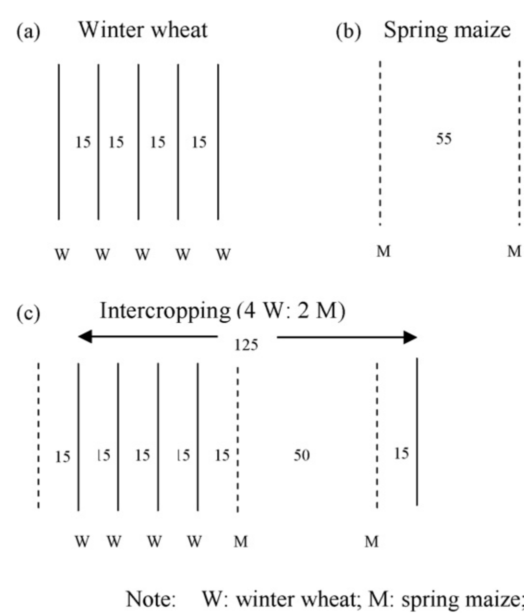

Fig. 1. Layout of winter wheat in monoculture (a), spring maize in monoculture (b) and in strip intercropping (c). *Note*: W, winter wheat; M, spring maize.

by hands in rows oriented north to south. Winter wheat was sown on 16 October 2003 and 11 October 2004, and spring maize was sown on 16 April 2004 and 2005 in two growing seasons. Each experimental plot was 40.8 m^2 (12 mL × 3.4 mW). Plots were surrounded by ridges of 10 cm to prevent runoff. Full irrigation was applied for both monoculture and intercropping with surface irrigation.

2.3. Reference evapotranspiration

Reference evapotranspiration was estimated by Penman-Monteith equation, as recommended by Allen et al. (1998):

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

where ET_0 is the reference evapotranspiration (mm day^{-1}), R_n the net radiation at the crop surface (MJ m^{-2} day^{-1}), G the soil heat flux density (MJ m^{-2} day^{-1}), T the mean daily air temperature at 2 m height (°C), u_2 the wind speed at 2 m height (m s^{-1}), e_s the saturation vapour pressure (kPa), e_a the actual vapour pressure (kPa), $e_s - e_a$ the saturation vapour pressure deficit (kPa), Δ the slope of the saturation vapour pressure curve (kPa $°C^{-1}$), and γ is the psychrometric constant (k Pa $°C^{-1}$).

Whether data used to calculate ET_0 were obtained from a weather station at the experimental station. The whether data including maximum temperature (T_{max}), minimum temperature (T_{min}), humidity (H), wind speed (u_2) and sunshine (h) during two growing seasons (2003–2004 and 2004–2005) are given in Table 1.

2.4. Computation of crop coefficient

Crop coefficient (K_c) was calculated with following equation:

$$K_c = \frac{ET_c}{ET_0} \quad (2)$$

where ET_c is the actual evapotranspiration (mm) and ET_0 is the reference evapotranspiration (mm). Here ET_c is estimated with soil water balance equation as follows (Hillel, 1998):

$$ET_c = P_e + I + U - R - D_w - \Delta S \quad (3)$$

where P_e is the effective precipitation (mm), determined by USDA soil conservation services method (Kuo et al., 2006; SCS, 1972), I the irrigation quota (mm), U the upward capillary flow into the root zone (mm), R the runoff (mm), D_w the downward drainage out the root zone (mm) and ΔS the change of soil water stored in soil layer of 0–100 cm (mm).

The upward and downward flow was estimated using Darcy's law (Kar et al., 2007; De Medeiros et al., 2005). Results indicated that the two items were negligible at the experimental site. Runoff was also negligible during the two growing seasons.

Soil water content was measured once a week with TRIME (IMKO, Ettlingen, Germany). Soil water content data were collected for every 10 cm interval in soil profile of 20–120 cm. Soil water content of soil layer of 0–20 cm was measured gravimetrically. Some measurements were added before and after irrigation and heavy rain events. TRIME access tubes were located between inner rows for wheat and maize in monocultures. In strip intercropping system, the tubes were located between two maize rows in maize

Table 1
Mean 10-day values of main weather factors at experimental site.

Month	10-Day	2003–2004					2004–2005				
		Mean T_{max} (°C)	Mean T_{min} (°C)	Mean H (%)	Mean u_2 (ms^{-1})	Sun. (h)	Mean T_{max} (°C)	Mean T_{min} (°C)	Mean H (%)	Mean u_2 (ms^{-1})	Sun. (h)
October	First	17.54	12.85	93.84	0.34	0.68	23.44	10.12	73.72	0.19	5.68
	Middle	18.76	8.27	70.56	0.66	3.69	22.30	9.75	71.64	0.19	5.59
	Last	23.30	9.79	57.96	0.50	7.87	18.97	8.65	68.42	0.21	4.16
November	First	13.48	5.34	74.90	0.41	2.59	18.89	7.95	69.40	0.27	5.55
	Middle	10.80	3.50	80.22	0.28	3.92	13.45	2.87	70.54	0.18	5.45
	Last	7.67	1.51	83.19	0.51	2.35	11.02	0.88	72.36	0.19	4.96
December	First	4.44	−0.98	81.67	0.58	3.33	11.82	1.93	66.93	0.44	5.07
	Middle	5.58	−3.09	74.04	0.39	3.59	5.66	1.09	81.92	0.34	1.62
	Last	9.97	−2.75	54.11	0.28	5.36	−1.30	−6.27	67.89	0.00	1.96
January	First	8.04	−1.37	57.23	0.34	2.70	2.78	−5.74	54.99	0.23	3.67
	Middle	4.95	−3.83	58.26	0.21	3.67	4.41	−6.27	69.08	0.06	3.59
	Last	5.17	−6.73	48.98	0.17	6.55	4.63	−3.56	56.39	0.52	3.65
February	First	9.29	−1.87	33.70	0.24	8.03	1.79	−3.97	56.45	0.60	2.72
	Middle	15.83	2.64	55.47	0.23	6.23	2.59	−3.40	72.30	0.31	2.76
	Last	13.89	5.13	62.83	0.53	4.93	8.71	−1.86	57.88	1.04	4.93
March	First	14.65	2.87	42.87	1.16	6.96	12.90	0.51	45.02	1.04	7.76
	Middle	15.09	5.85	69.29	0.90	3.92	12.25	1.75	48.16	0.66	6.25
	Last	18.04	7.74	64.52	0.57	4.93	17.07	5.86	61.32	0.65	7.32
April	First	20.39	8.23	51.47	0.58	8.40	21.26	9.68	59.06	1.08	6.34
	Middle	26.21	14.23	64.14	0.47	7.82	23.88	11.20	47.64	1.00	8.98
	Last	22.65	12.39	69.36	0.52	6.57	28.39	15.24	59.00	0.55	9.91
May	First	25.27	14.40	65.26	0.45	8.47	24.56	13.63	62.46	0.52	8.62
	Middle	27.47	16.09	62.15	0.59	8.42	24.09	15.22	77.68	0.36	5.66
	Last	29.02	16.43	62.90	0.36	7.85	29.58	18.47	63.46	0.56	7.95
June	First	27.90	16.71	65.13	0.21	5.69	32.00	20.64	60.11	0.49	7.19
	Middle	30.33	19.64	73.99	0.31	5.24	36.91	23.34	54.93	0.45	7.01
	Last	34.04	22.86	74.24	0.53	7.56	34.24	23.37	69.49	0.28	8.24
July	First	33.80	21.89	73.89	0.34	6.78	31.39	23.56	80.14	0.18	7.35
	Middle	28.52	22.23	90.37	0.29	2.52	32.71	24.50	85.69	0.03	5.88
	Last	32.11	24.09	84.11	0.33	4.24	30.69	23.78	89.44	0.07	5.87
August	First	31.59	23.12	84.83	0.27	4.47	32.11	23.49	83.55	0.02	7.20
	Middle	27.21	19.79	84.76	0.33	4.33	31.46	23.00	82.34	0.00	7.00
	Last	29.36	20.68	82.57	0.25	4.45	28.24	18.68	84.40	0.03	6.50

strip, between inner rows in wheat strips and between the wheat and maize strip, respectively.

2.5. Water-use efficiency and land equivalent ratio (LER)

WUE was calculated using the following equation (Zhang et al., 2007a):

$$\mathrm{WUE} = \frac{Y}{ET_c} \qquad (4)$$

where WUE is the water-use efficiency (kg ha^{-1} mm^{-1}), Y the grain yield (kg ha^{-1}), and ET_c is the total actual evapotranspiration over the whole growing season (mm).

To evaluate yield performance of strip intercropping and monoculture, LER was used and determined as follows (Vandermeer, 1989; Willey, 1985):

$$\mathrm{LER} = \frac{Y_{WI}}{Y_{WM}} + \frac{Y_{MI}}{Y_{MM}} \qquad (5)$$

where Y_{WM} and Y_{WI} are grain yields of winter wheat in monoculture and intercropping (kg ha^{-1}), respectively; Y_{MM} and Y_{MI} are grain yields of spring maize in monoculture and intercropping, respectively (kg ha^{-1}).

2.6. Leaf area index (LAI) and aboveground dry mass

LAI of wheat and maize were measured after emergence at 7–10 days interval during the whole growing season. For winter wheat, a sample area of 400 cm^2 (20 cm × 20 cm) is selected and all plants in the area are colleted for each experimental plot. Leaf length and the greatest leaf width were measured with ruler, and leaf area is determined by following formula: leaf area = leaf length × the greatest leaf width × 0.80. LAI is set as the ratio of total leaf area to land area over an experimental plot. For spring maize, 10 sample plants are selected for each plot and area of each leaf is measured with an area meter (model LI-3100, Li-Cor, Inc., Lincoln NE). LAI is determined with the same definition as for winter wheat. For intercropping system, LAI of wheat and maize is measured

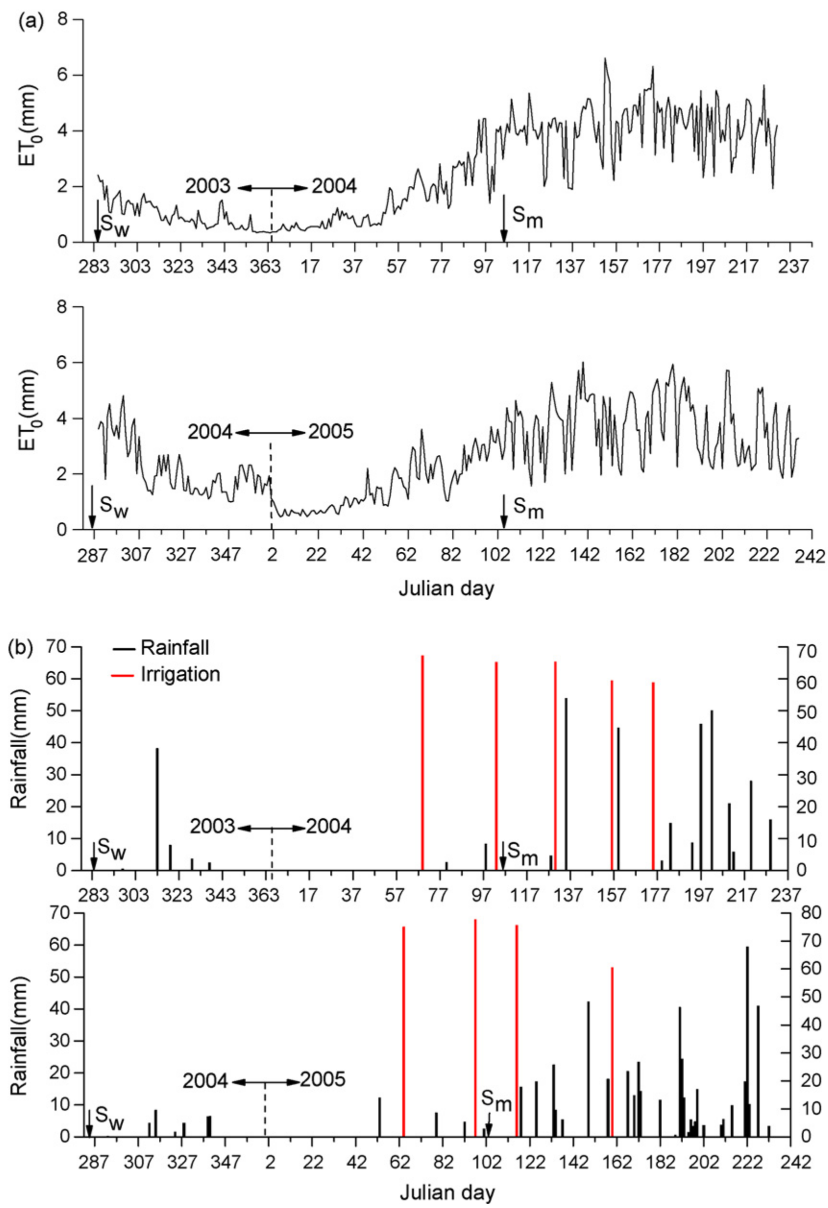

Fig. 2. Daily ET_0 (a), irrigation and rainfall (b) during 2003–2004 and 2004–2005 growing seasons. Arrows indicate sowing time of wheat (S_w) and maize (S_m).

separately, and total LAI is set as the sum of wheat LAI and maize LAI.

For determining aboveground dry biomass, a 1-meter sample section of plants were collected for each plot at a 7–10 days interval during the whole growing season. The final grain yields were determined by harvesting all plants in a 8 m^2 (4 mL × 2mW) sample area for each plot. The grain yield of each plot was determined by weighting all grains after natural drying with moisture content of about 12%.

3. Results and discussion

3.1. Reference evapotranspiration and crop evapotranspiration

Rainfall, irrigation and reference evapotranspiration (ET_0) over two growing seasons, set as form sowing of winter wheat to harvesting of spring maize, are presented in Fig. 2. For the 2003–2004 and 2004–2005 seasons, precipitation was 531.5 and 394.5 mm, irrigation 289 and 316 mm, and ET_0 820 and 765 mm, respectively. Daily ET_0 varied in 0.46–6.02 mm, with average value of 2.62 mm day^{-1} during 2003–2004 growing season. In 2004–2005 growing season, the daily ET_0 varied in 0.34–6.62 mm, with a mean value of 2.45 mm day^{-1}.

Fig. 3 shows the changes of daily actual crop evapotranspiration in the intercropping and monocultures. During the growing season, average actual evapotranspiration rate in the intercropping system was slightly higher than that in the monocultures.

3.2. LAI and aboveground biomass

Variations of LAI for winter wheat and spring maize in monoculture and in intercropping are shown in Fig. 4. The wheat LAI in the intercropping was less than that in monoculture. But the difference between maize LAI in intercropping and LAI in monoculture is negligible. Changes of LAI were similar in two growing seasons.

Aboveground dry biomass in intercropping was slightly greater than that in monocultures because of edge-row effects (Fig. 5). The accumulating rate of dry biomass for wheat is relatively less before 100th Julian day (JD), and thereafter markedly increased. The dry

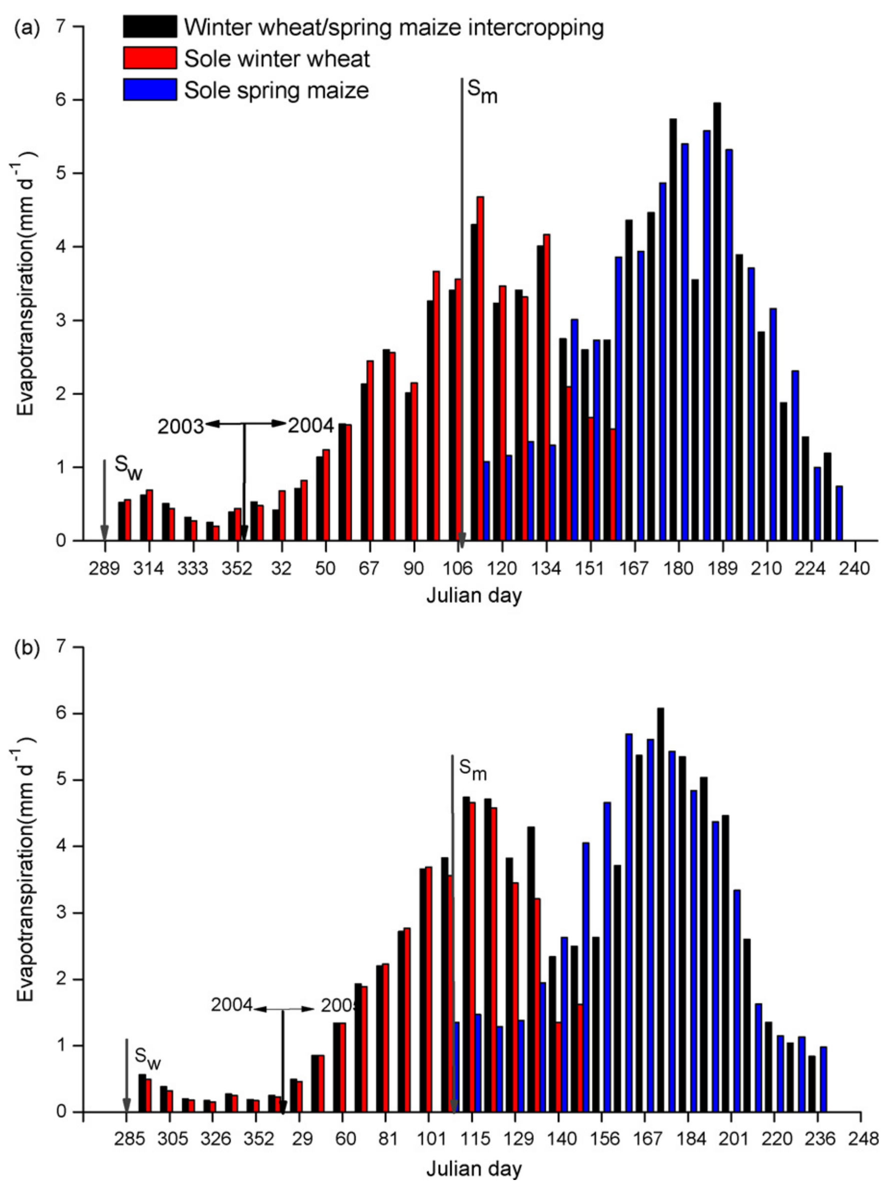

Fig. 3. Daily evapotranspiration of winter wheat and spring maize in monocultures and intercropping during 2003–2004 (a) and 2004–2005 growing season (b).

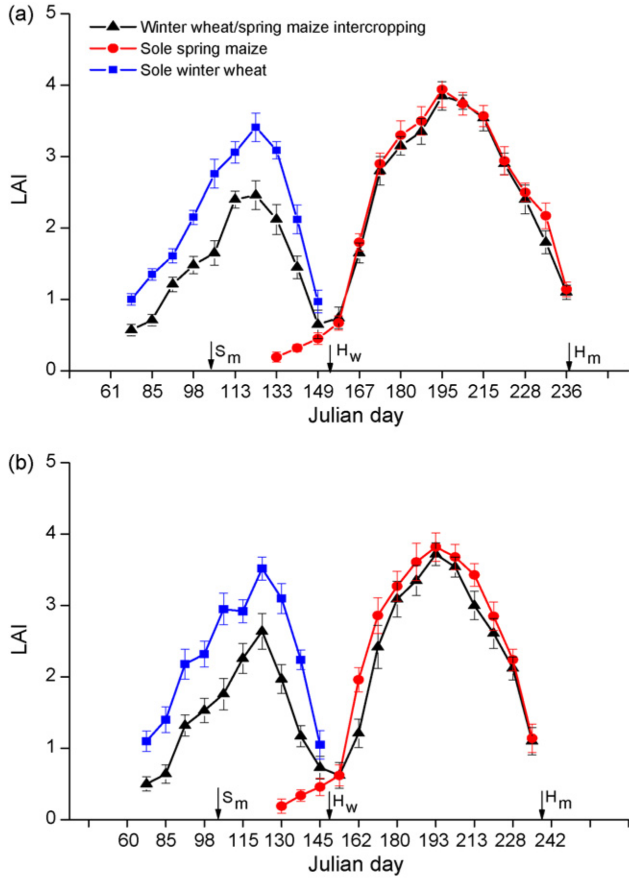

Fig. 4. Leaf area index (LAI) of winter wheat and spring maize in monocultures and intercropping during 2003–2004 (a) and 2004–2005 growing season (b). Arrows indicate sowing time of maize (S_m) and harvesting time of wheat (H_w) and maize (H_m).

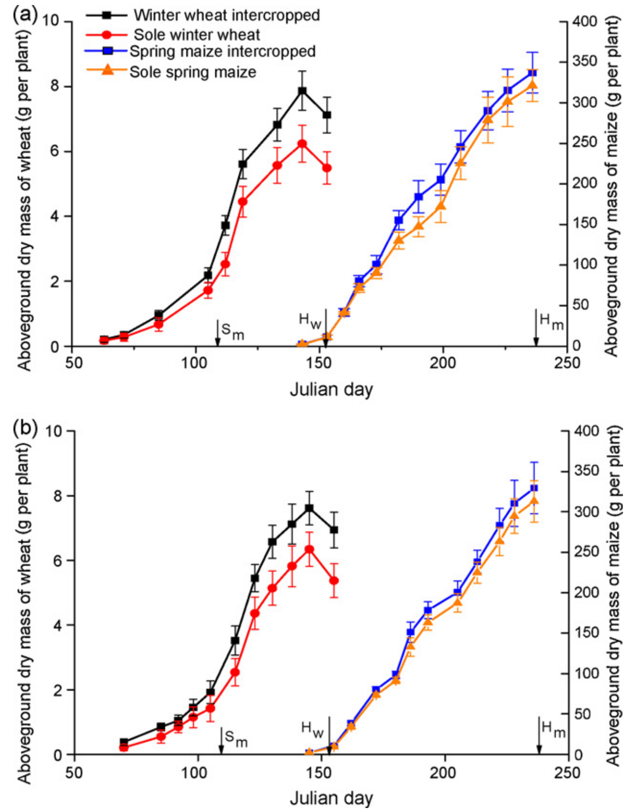

Fig. 5. Aboveground dry mass of winter wheat and spring maize in monocultures and intercropping for 2003–2004 (a) and 2004–2005 (b) growing season.

biomass did not change for winter wheat both in intercropping and in monoculture during the 10 days before harvest. Dry biomass of maize in monoculture and in intercropping increased almost linearly during the whole growing season.

3.3. Crop coefficient

Fig. 6 shows the changes of crop coefficient (K_c) for winter wheat (Fig. 6a and b) and spring maize (Fig. 6c and d) in monoculture over two seasons. The crop coefficients presented at four growing stages were fitted by a polynomial function and are also given in Fig. 6. Duration of initial, development, mid and late season for winter wheat was 90, 60, 50 and 30 days, respectively. Crop coefficient value of winter wheat in monoculture was 0.26, 1.09 and 0.41 at initial, mid and late season in 2003–2004 season, respectively. In 2004–2005 season, K_c value of winter wheat in monoculture was 0.36, 1.19 and 0.28 at initial, mid and late season, respectively.

Duration of initial, development, mid and late season for spring maize was 30, 30, 40 and 30 days, respectively. In monoculture, average K_c value of spring maize was 0.36, 1.15 and 0.27 in 2003–2004 season, and 0.37, 1.18 and 0.22 in 2004–2005 season at initial, mid and late season, respectively. Some literatures showed that value range of K_c of winter wheat in monoculture was 0.20–0.60, 1.10–1.35 and 0.20–0.80 at initial, mid and late season in Northern China, respectively (Chen et al., 2006; Duan et al., 2004; Liu and Pereira, 2000). For spring maize in monoculture, value range of K_c was 0.28–0.45, 1.12–1.18 and 0.25–0.40 at initial, mid and late season in Northern China, respectively (Duan et al., 2004). The results of crop coefficients get in this study were consistent with those shown in literature.

Fig. 7 shows crop coefficient for wheat/maize strip intercropping. At initial stage of winter wheat, K_c was less, with an average value of 0.31 and 0.39 in 2003–2004 and 2004–2005 growing season, respectively. Thereafter, K_c increased quickly with winter wheat's quicker growth, and K_c value at mid-stage of wheat was 1.14 and 1.23 for the two seasons, respectively. During late-stage of wheat, K_c decreased as wheat leaves senescence, with a value of 0.65 and 0.70 at harvesting for two seasons. After wheat's harvest, crop coefficient in the intercropping system increased quickly again with maize's quicker growth. At the mid-stage of maize, average K_c in the intercropping was 1.24 and 1.25 for the two seasons, respectively. At late-stage of maize, K_c decreased again with maize leaves senescence. At maize's harvest, K_c decreased to about 0.27 and 0.21 for two seasons, respectively. The crop coefficient in the intercropping was slightly higher than that in the monocultures because the evapotranspiration in intercropping system was higher than that in monocultures as shown in Fig. 3. A polynomial function was fitted to the relationship between JD and K_c in the intercropping (Fig. 7).

The curve in Fig. 7 shapes as two-peaks. Analysis showed that the first peak of K_c is related closely to the quick development of winter wheat, and the second to the spring maize. Judging together with Figs. 6 and 7, it may be concluded that what goes on in the intercropping can be understood very well from what goes on in the monocultures. Therefore, it is possible to predict the time course of K_c in an intercropping from known time courses of K_c in monocultures.

Crop coefficient is related closely to crop type and management practice, which may influence plant development rate and ground coverage (Allen et al., 1998; Williams and Ayars, 2005). Many

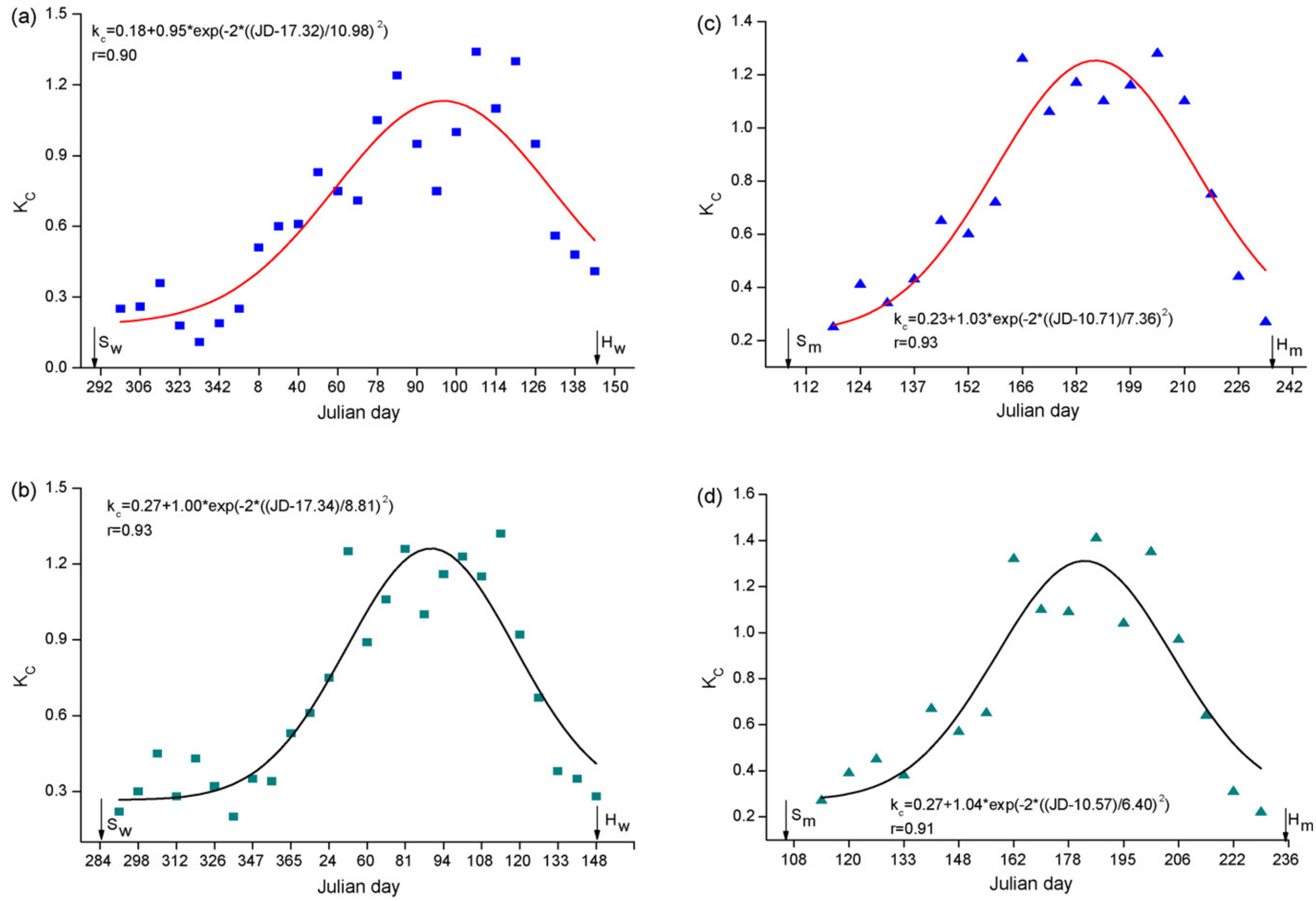

Fig. 6. Crop coefficient as function of Julian day for winter wheat (a and b) and spring maize (c and d) in the monocultures during 2003–2004 (a and c) and 2004–2005 (b and d) growing season.

studies have indicated that K_c was related to LAI, percentage of ground cover (Al-Kaisi et al., 1989; De Medeiros et al., 2001; Heilman et al., 1982) and DAE (days after emergence) (De Medeiros et al., 2001). In this study, the K_c in the intercropping and in the monocultures was significantly correlated to the JD.

3.4. Water-use efficiency and land equivalent ratio

Yield, WUE and LER in the winter wheat/spring maize intercropping system were shown in Table 2. Average yield of winter wheat in the intercropping for two seasons was 4516.16 kg ha^{-1}, about 62% less than that in the monoculture. Average yield of spring maize in intercropping for two seasons was 9900.67 kg ha^{-1}, only 5% less than that in the monoculture. But compared with yields of spring maize and winter wheat in monoculture, the total yield (wheat + - maize) of intercropping may raised by 39% and 98%, respectively, indicating that the winter wheat/spring maize strip intercropping has obvious advantage in yield.

Average WUE in winter wheat/spring maize strip intercropping system was 21.72 kg ha^{-1} mm^{-1} over 2003–2004 and 2004–2005 seasons, which was 23% less than one in monoculture spring maize, but 4% greater than one in monoculture winter wheat. Compared to the maize and wheat in monoculture, the wheat/maize intercropping system raised yield significantly, although no obvious WUE improvement.

In intercropping system, WUE was influenced by plant density and crop proportion (Morris and Garrity, 1993). In the wheat/maize intercropping system, the homogenized row distances (HRDs), which are the average distance between rows of one of the component crops in the intercropping (Zhang et al., 2007b), were

Table 2
Yield, water-use efficiency and land equivalent ratio in the monocultures and intercropping.

Season	Parameter	Spring maize		Winter wheat		Intercropping sum
		Monoculture	Intercropping	monoculture	Intercropping	
2003–2004	ET_c (mm)	357.90	–	354.13	–	680.48
	Yield (kg ha^{-1})	10563.90	9969.19	7373.61	4594.07	14563.26
	WUE (kg ha^{-1} mm^{-1})	29.52	–	20.82	–	21.40
	LER	–	0.94	–	0.62	1.56
2004–2005	ET_c (mm)	382.79	–	347.70	–	650.60
	Yield (kg ha^{-1})	10234.15	9832.15	7284.04	4498.25	14330.40
	WUE (kg ha^{-1} mm^{-1})	26.74	–	20.95	–	22.03
	LER	–	0.96	–	0.62	1.58

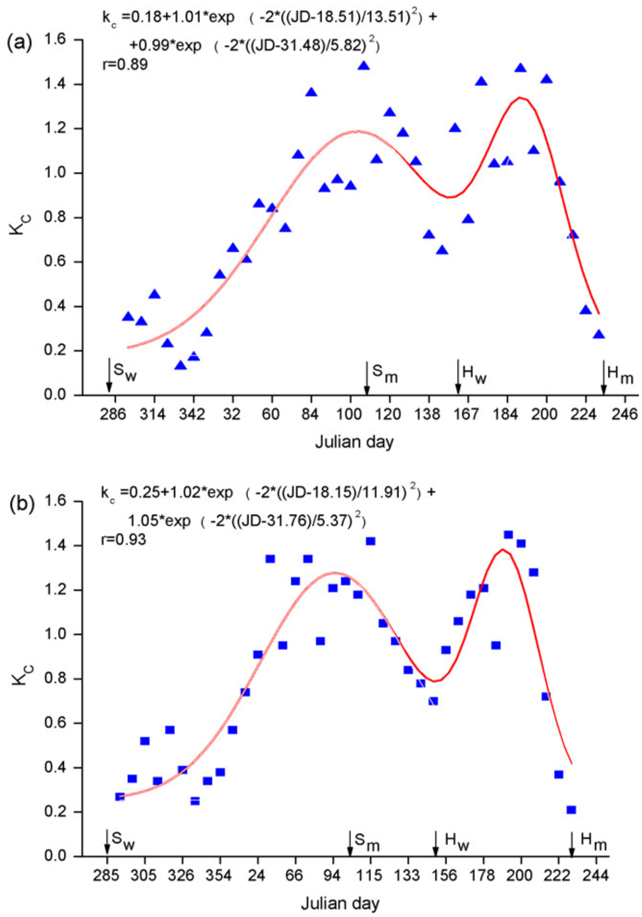

Fig. 7. Crop coefficient as function of Julian day for winter wheat/spring maize intercropping during 2003–2004 (a) and 2004–2005 (b) growing season.

31.25 and 62.5 cm for wheat and maize, respectively. Therefore, the density in the intercropping was about 50% of that in the monoculture for wheat, and about 88% for maize. Because density of wheat was reduced more greatly, the yield of wheat in intercropping decreased more obviously, which led to a less WUE in the intercropping. To improve WUE in the winter wheat/spring maize intercropping, the planting proportion of winter wheat and spring maize should be adjusted appropriately.

It is very difficult to separate water use by two crops during the co-growth period (Adiku et al., 2001; Morris and Garrity, 1993). Works did not be done in this study to investigate water uses by the wheat and maize separately in the intercropping system. The sap flow technique, which may measure directly transpiration rate of each plant, may be a helpful tool to study water absorption by each crop in the intercropping system.

LERs in the winter wheat/spring maize intercropping system were 0.95 and 0.62 for spring maize and winter wheat, respectively. Although grain yields of the two crops in the intercropping were less than those in the monocultures, the intercropping improved total land productivity as supported by greater LER (1.57), which means that 57% more land in the monocultures is required than that in the intercropping for producing same yield. Therefore, the winter wheat/spring maize intercropping system may improve land-use efficiency considerably.

4. Conclusions

The curve of crop coefficients in the winter wheat/spring maize strip intercropping was two-humped, indicating that the first peak in K_c was due to wheat, and the second to maize. Total grain yield (wheat + maize) in the winter wheat/spring maize intercropping rose by 39% and 98% while compared to maize and wheat yields in the monocultures, respectively. Average WUE in the intercropping system was 21.72 kg ha^{-1} mm^{-1}, which was less than that of maize in monoculture, but slightly greater than that of wheat in monoculture. Therefore, the winter wheat/spring maize intercropping system may be helpful to ensure grain supply and is suitable to practice in North China.

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