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Water use and crop coefficient of the wheat–maize strip intercropping system for an arid region in northwestern China

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ABSTRACT

Relay strip intercropping of spring wheat and maize is practiced on a large scale in arid regions of northwestern China. In this study, a field experiment was carried out during 2012 and 2013 growing seasons to examine water use and crop coefficient of this system in an arid environment. The experiment comprised three treatments: sole-cropped wheat, sole-cropped maize, and wheat–maize intercropping. The grain yields of both intercropped wheat and maize were enhanced by intercropping. The gross economic profit for wheat–maize intercropping was 16.4% lower than that of sole maize and 95.4% higher than that of sole wheat. The overall land use efficiency was improved by intercropping. The time course of leaf area index in intercropping had the similar trends to those in sole crops with relatively low values, which never exceeded 3.0 $m^2\,m^{-2}$ throughout both growing seasons. Compared to weighted means of the sole-cropping systems, wheat–maize intercropping used 26% and 24% more water in 2012 and 2013, respectively. The water-use efficiency of intercropping was nearly the same as the weighted means of the sole crops. Due to the incomplete groundcover in intercropping plots, more water was consumed as soil evaporation. Averaged over two seasons, the ratio of soil evaporation to actual evapotranspiration was 33.4, 20.7 and 24.1% for intercropping system, sole-cropped wheat and sole-cropped maize, respectively. Crop coefficient ($K_{c)}$ of sole-cropped wheat was 0.19 ± 0.02, 1.05 ± 0.07, and 0.42 ± 0.09 at the initial, mid and late season in two seasons, respectively. K_c value of the sole-cropped maize was 0.22 ± 0.03, 1.10 ± 0.06 and 0.60 ± 0.02 at the initial, mid and late season, respectively. The K_c values of the wheat–maize intercropping system varied in 0.21 ± 0.03, 0.89 ± 0.05, and 0.78 ± 0.06 at the initial, middle and late wheat growing season, and in 0.85 ± 0.03 and 0.61 ± 0.01 at the middle and late maize growing season, respectively. Therefore, longer growing season and incomplete ground cover are the main factors that resulted in higher water use for wheat–maize intercropping compared to sole crops. Results of this study can help to improve the irrigation efficiency for the wheat–maize strip intercropping system.

1. Introduction

Intercropping can improve grain yield through more efficient use of agricultural sources such as nutrient, water, heat and radiation (Willey, 1990; Rao and Mathuva, 2000; Thorsted et al., 2006; Lithourgidis et al., 2011). It may also be a means to address some of the major problems associated with modern farming, including moderate yield, pest and pathogen accumulation, soil degradation and environmental deterioration, thereby helping deliver sustainable and productive agriculture (Vandermeer, 1989; Lithourgidis et al., 2011; Brooker et al., 2015). In northern high latitude areas, there is typically one crop per year due to short growing seasons. Many relay intercropping systems have been developed to extend the growing season in recent years (Coll et al., 2012; Mao et al., 2012). Wheat–maize intercropping is widely practiced in the Hetao Irrigation District in Inner Mongolia (about 40°19′–41°18′N, 106°20′–109°19′E) and the Hexi Corridor in Gansu Province (about 37°15′–41°30′N, 92°21′–104°45′E), China. In this system, the strips of wheat are sown in late March and space is left open between

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the wheat strips to enable to sow maize one month later. Wheat is harvested in mid-July, leaving approximately 80 co-growing days for the two crops (Zhang and Li, 2003; Li et al., 2006). Local farmers usually irrigate crops based not on crop water requirements but on irrigation times. According to local practices, more than 150 mm autumn water in October is applied in every year to ensure the seedling growth of crop to be planted next year; sole wheat is not irrigated until early May and sole maize is not irrigated until late June (Xu et al., 2010; Gao et al., 2014). The crops are irrigated about every 20 days after the first irrigation is applied, and sole-cropped wheat and maize received 3–4 and 4–5 times of irrigation, respectively, during their growing seasons. In contrast, wheat–maize intercropping received 6–7 times of irrigations and thus consumes much more water (Fan et al., 2013). Therefore, estimating water use and determining crop water requirement accurately are necessary for optimal irrigation schedules to ensure the yield stability of the wheat–maize intercropping system.

Water use by intercropping was commonly compared against the weighted means of water use by their sole counterparts with the proportions of soil area occupied by each crop in intercropping system as weighted-mean coefficients (Willey, 1990; Morris and Garrity, 1993; Mao et al., 2012). Water-use efficiency was compared in the same way. Morris and Garrity (1993) summarized that water use by intercrops differed from that by sole crops by only −6 to 7% in most cases, and the water-use efficiency of an intercropping system was greater than that of monoculture by 4–99%. However, there were also some studies indicating that the intercrops attained their greater yields at the price of consuming much more water and did not improve water-use efficiency (Grema and Hess, 1994; Gao et al., 2009; Yang et al., 2011; Coll et al., 2012). The loss of water from the soil surface through evaporation is a major component in the soil water balance of the agricultural systems. This is particularly the case for sparse canopies (Allen, 1990; Daamen et al., 1995; Wallace et al., 1999; Kang et al., 2003). The full ground cover is usually hardly achieved in the relay strip intercropping systems resulting in a large amount of water loss through soil evaporation. However, there are few studies on this issue.

The crop coefficient (K_c), defined as the ratio of actual crop evapotranspiration (ET_c) to reference crop evapotranspiration (ET_0), is a very important parameter for evaluating the crop water use characteristics. The FAO irrigation and drainage paper presented values of K_c for a large number of crops under the standard climatic conditions (Allen et al., 1998). The localized value of K_c is essential to improving planning and efficient irrigation management in many field crops (Allen et al., 1998; Kar et al., 2007). The K_c values of the sole-cropped wheat and maize in the Hexi corridor and Hetao irrigation district have been previously evaluated (Zhao et al., 2010; Zhang et al., 2013; Yang et al., 2014). However, little attention has been paid to investigating the seasonal variation of the K_c values for the wheat–maize intercropping system.

The objectives of this study were to: (i) compare the water use and water-use efficiency of wheat–maize intercropping with those of sole-cropped wheat and maize; (ii) determine the ratios of soil evaporation to actual crop evapotranspiration for different cropping systems; (iii) and investigate the crop coefficients of the wheat–maize intercropping system and its sole counterparts. These measurements can be used to improve irrigation scheduling and regional water allocating in arid regions.

2. Materials and methods

2.1. Experimental site

Field experiments were conducted in 2012 and 2013 at the Shahaoqu Experimental Station (40°54′N, 107°09′E, and altitude 1035 m) in the Hetao Irrigation District, which is one of the three largest irrigation districts in China and located in the west part of Inner Mongolia Autonomous Region, China. Based on the long-term (1961–2010) weather data of the site, the mean annual air temperature is 7.7 °C with a maximum monthly mean daily air temperature of 22.8 °C in July and a minimum monthly mean daily air temperature of −10.2 °C in January. There are 135–150 frost-free days and 3100–3300 h sunshine duration per year. The mean annual precipitation is 135 mm, 66% of which occurs over July through September. The mean annual pan evaporation (the E_{20} pan) is approximately 2100 mm, much larger than the precipitation. Meteorological data (air temperature, relative humidity, wind speed at 2-m-height, solar irradiance and precipitation) were recorded hourly at the onsite agriculture meteorological station (Vantage Pro2, Davis Instruments, Hayward, CA, USA). A summary of the meteorological data during the two crop growth seasons are presented in Table 1. Air temperature in 2013 was slightly greater than that in 2012 for every month except April, while relative humidity in 2012 was greater than that in 2013 in May through September due to the larger amount of precipitation that occurred in 2012. Total rainfall during the growing season was 199.8 mm in 2012, which was 39.7% more than the long-term total, while that was only 87.6 mm in 2013, which was 38.7% less than the long-term total.

The study area is located in the upper reaches of the Yellow River. The soils are alluvial silt sediments. The particle size distribution and field capacity of the soil in the 0–1 m profile are listed in Table 2. Before the first wheat growing season, available nitrogen (N), phosphorus (P), potassium (K), and organic matter contents in the 0–0.2 m soil layer were 104.1, 55.4, 121.1, and 9800 mg kg^{-1}, respectively, and those in the 0.2–0.6 m layer were 74.1, 17.6, 79, and 4500 mg kg^{-1}, respectively.

2.2. Experimental design

The experimental design was a randomized complete block with three treatments replicated for three times. The three treatments were: wheat sole-cropping, maize sole-cropping, and wheat–maize strip intercropping. The selected spring wheat and maize cultivars were 'Yong-liang 4' and 'Nei-dan 314', respectively. Wheat was planted on 25 March 2012 and was harvested on 15 July, and maize was planted on 23 April and harvested on 21 September. In 2013, the dates of sowing were 19 March for wheat and 21 April for maize, and the dates of harvesting were 12 July for wheat and 20 September for maize. Sole wheat was planted with a density of 6,670,000 plants ha^{-1} and an inter-row distance of 0.15 m, and sole maize was planted with a density of 83,300 plants ha^{-1}, an inter-row distance of 0.40 m and an intra-row distance of 0.30 m. Wheat–maize intercropping in this study was replacement intercropping (several wheat rows were replaced by maize rows). The overall proportional density of each crop species was equal in both the monoculture and intercropping treatments. The distance between the wheat and maize strips was 0.275 m. Each intercropping strip was designed with six wheat rows (0.9 m wide strip) or two maize rows (0.8 m wide strip) (Fig. 1). The plot size was 5.1 m wide and 10 m long. There were three intercropping strips in each intercropping plot. Wheat and maize were fertilized with 240 and 360 kg N h^{-1}, respectively. The N and P fertilizers were urea (46% N) and diammonium phosphate (18% N and 44% P_2O_5), respectively. The full doses of P and half doses of N were evenly broadcast before seeding to the sole-cropped and intercropped wheat, and the remaining 50% N was top-dressed at the first irrigation. The full doses of P and half doses of N were incorporated into the soil of the sole-cropped and intercropped maize, and the remaining 50% N was applied equally at the elongation and pre-tasseling stages with the corresponding irrigations. Full irrigation was applied to prevent water stress, and details on the irrigation dates and irrigation amounts in 2012 and 2013 are listed in Table 3.