Evaluating water use advantage of wheat-maize relay intercropping under rainfed condition using an improved approach

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Abstract

Accurately assessing water consumption and water use efficiency in intercropping systems relative to sole crop systems is important for planting system planning. This study was conducted to improve water use evaluation method for wheat/maize (Triticum aestivum L./Zea mays L.) intercropping under rainfed conditions. Field experiments were conducted from 2014 to 2016 in Yangling, Shanxi Province, China. Three cropping patterns were tested: sole wheat, sole maize, wheat/maize intercrops. Method for evaluating water use advantage in intercropping was improved by considering water consumption of sole crops during the fallow period. Results showed that intercropping grain yield was higher than sole cropping yield. Before revising the water use period to account for water use during the non-crop period, the intercropping system had 20.3% greater water use, but 18.7% lower water use efficiency than the sole cropping system. After the revision accounting for non-growth period water use, intercropping had 8.1% less water use than sole cropping, and 5.3% greater water use efficiency. After revising the water use period, intercropped wheat used 24.5% less water and the intercropped maize used 11% more water than the corresponding sole crops, and the water use efficiency of intercropped wheat was 32.4% greater than sole wheat water use efficiency. The revised method accounting for water use during the non-growth portion of the crop production season resulted in a more objective evaluation of water utilization in the intercropping system. Wheat/maize intercropping increased both yield and water use efficiency, which is especially important for areas with limited water.

Introduction

Farmland has degraded in many regions of the world in response to socio-economic development and rapid growth in grain production. Many countries in the world have adopted fallow farming policies in order to protect the productivity of cultivated land and to ensure sustainable agricultural development. Those countries include the United States (Nielsen et al., 2005; Singh et al., 2011), Spain (Moret et al., 2006), and Australia (Cann et al., 2020). Such policies include the Conservation Reserve Program (CRP) in the United States and the land reserve plan in the European Union. China has given national attention to the quality of cultivated land in recent years, and an ecological fallow policy was proposed at China's 13th Five-Year Plan and 2016 No. 1 document. Currently, the area employing fallow farming has reached 2.6 million ha.

One of the most important reasons for using fallow in China is water shortage. For example, Hebei Province (North China Plain) has a groundwater funnel area due to groundwater over-exploitation (Wang et al., 2008; van Oort et al., 2016; Min et al., 2015). Therefore, some areas have implemented an ecological fallow policy. Under such a policy, the traditional two-crop rotation has been replaced by a planting practice of one season of fallow followed by the next season planted with a sole crop without any irrigation (i.e., rainfed). Because food security cannot be ignored, it is imperative to understand how to decrease the yield loss associated with fallow. A previous study showed that fallow in the North China Plain increased water resources and restored the groundwater level, but resulted in a 13% decrease in annual grain yield (Xiao et al., 2017). Relay strip intercropping is a system in which a second crop is planted into reserved areas between strips of the first crop during the late growth period of the first crop. As such, the different crops only partially overlap during the growing period. Compared with sole cropping, relay intercropping could increase grain yield and production stability through the complementation of temporal and spatial niche differentiation (Li et al., 2007; Li et al., 2020; Raseduzzaman et al., 2017; Sileshi et al., 2012). Fallow may increase soil evaporation or increases erosion (Nielsen and Vigil, 2017; Wischmeier, 1959). Fallow periods frequently result in soil quality degradation due to soil erosion that occurs with frequent rainfall and a reduction in soil surface cover (Huang et al., 2013; Iwara, 2014). Relay intercropping can extend the length of the period in which crops are grown in a single season as compared with sole crop production, increase ground cover, and reduce soil water evaporation and soil erosion compared with sole cropping. Therefore, relay intercropping may be a suitable production practice to employ as fallow policy is implemented.

The primary purpose of fallow is to accumulate soil water for future crop use (Aase and Pikul, 2000; Hammel et al., 1981; Al-Mulla et al., 2009; Nielsen and Calderóm. 2010). Previous comparison studies of cropping systems have generally only considered the non-growth water consumption period between crops in the intercropping system, but did not consider the non-growth water consumption of sole crop systems (Fan et al., 2013; Gao et al., 2009; Mao et al., 2012). In order to correctly understand and quantify the water-saving capacity of fallow from an ecological perspective, we believe that both the water consumption in the growing season and the water stored in the soil after harvesting the early-maturing crop should be considered. Therefore, it is necessary to consider water consumption during the period between the planting or harvesting of the two crops in both the intercropping and sole cropping production systems. Under such a premise, we must reconsider the issue of water consumption evaluation in relay intercropping to provide a reference for selecting fallow measures.

Researchers have used changes in water use (WU) and water use efficiency (WUE) as indicators reflecting the water use of intercropping systems relative to sole cropping systems (Mao et al., 2012; Morris and Garrity, 1993; Ren et al., 2019; Wang et al., 2015a, b; Willey, 1990). Previous studies have shown that the WUE of an intercropping system is significantly greater than the WUE of sole crops (Morris and Garrity, 1993; Walker and Ogindo, 2003). However, other studies have shown reduced WUE for the intercropping system (Gao et al., 2009; Rees, 1986a, b; Wang et al., 2015a). Some previous studies only compared the overall water use of monocropping and intercropping and did not explore how water distribution in the system occurred. Namely, little attention has been given to investigating WU and WUE of the individual component crops of an intercropping system. Therefore, it is necessary to quantify and evaluate WU and WUE of the individual component crops in the intercropping system.

The objectives of this study were to 1) assess the impact of accounting for non-growth period water use on total production season WU and WUE of wheat and maize grown in an intercropping system and as sole crops; and 2) determine yield, water use, and water use efficiency advantages for intercropped wheat and maize production compared with sole crops.

Materials And Methods

Theory of ΔWU and ΔWUE

ΔWU originally proposed by Morris and Garrity (1993) was used to assess the water use advantage of intercropping compared with sole cropping. ΔWU is quantified by the difference between the actual water use in intercropping and the expected water use in intercropping considering the grain yield. ΔWU was calculated as follows:

$$\Delta \mathrm{WU} = \frac{\mathrm{WU_I}}{\mathrm{P_W WU}_{SW} + \mathrm{P}_M \mathrm{WU}_{SM}} - 1$$

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where WU_I, WU_{SW}, and WU_{SM} are the seasonal water use in intercropping, sole wheat, and sole maize (mm), respectively; P_M is the proportion of intercropped area initially allocated to maize, and P_W is the same for wheat. A positive value of ΔWU indicates that more water is consumed by intercropping to produce a given yield than is consumed to produce the same yield with the sole cropping system; a negative value in ΔWU indicates that less water is consumed by intercropping to produce a given yield than is consumed to produce the same yield with the sole cropping system.

Mao et al. (2012) pointed out that precise land cover values are difficult to identify unequivocally by observation because the edges of the leaf canopies of competing crops are fractal and difficult to identify due to intermingling. Therefore, the calculation of ΔWU was modified by Mao et al. (2012). They used the partial land equivalent ratio of crops A and B as weights in the formula for WU.

$$\Delta \mathrm{WU} = \frac{\mathrm{WU_I}}{\mathrm{PLER_W WU}_{SW} + \mathrm{PLER_M WU}_{SM}} - 1$$

2

where $PLER_W$ and $PLER_M$ are the partial land equivalent ratios of wheat and maize in intercropping.

Previous comparison studies of cropping systems have generally only considered the non-growth water consumption period between crops in the intercropping system and did not consider the non-growth water consumption of sole cropping systems (Fan et al., 2013; Mao et al., 2012; Yang et al, 2011). This resulted in differences in the length of the water consumption period, underestimating the water consumption of the sole crop, and in turn overestimating the WUE of sole crops.

In previous studies reported by Morris and Garrity (1993) and Mao et al (2012), the water use in bare ground between the crop strips in intercropping was considered in intercropping, but the water use in bare ground (during the period before the planting of the later-maturing crop or the period from the early-maturing crop harvest to the late-maturing crop harvest) was not considered in sole cropping. As shown in Fig. 1, the water use calculation period for the sole wheat was A, and that of sole maize was D, but the water use calculation period for intercropped wheat was A + B, and that of intercropped maize was C + D. Therefore, the calculation period for the sole cropping system was A + D, but the calculation period for the intercropping system was A + B + C + D. Hence, the length of the calculation period for the sole cropping system was shorter than that for the intercropping system. The length of the periods differed which may affect the determination of actual water use of sole cropping system.

When the water use advantage of intercropping compared with sole cropping is assessed, the calculation periods for water use are essentially the same between the two cropping systems. Even though water consumption (evaporation) in bare soil in both intercropping and sole cropping contributes nothing towards grain production, it should be considered for each cropping system.

Therefore, in our study, we revised the calculation periods for water use in both the intercropping system and the sole cropping system.

The water use of sole wheat and sole maize was calculated as:

$$\mathrm{WU}_{\mathrm{SW}} = \mathrm{WU}_{\mathrm{SW,g}} + \mathrm{WU}_{SW,n}$$

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$$\mathrm{WU}_{\mathrm{SM}} = \mathrm{WU}_{\mathrm{SM,g}} + \mathrm{WU}_{SM,n}$$

4

where WU_{SW} and WU_{SM} are the total water use (mm) of sole wheat and sole maize, respectively; $WU_{SW,g}$ and $WU_{SM,g}$ are water use of sole wheat and sole maize in the growth period (from planting to harvest of wheat for sole wheat, from planting to harvest of maize for sole maize), respectively; and $WU_{SW,n}$ and $WU_{SM,n}$ are water use of sole wheat and sole maize in the non-growth period (from wheat harvest to maize harvest for sole wheat, from wheat planting to maize planting for sole maize), respectively.

ΔWU_w was used to evaluate the difference between the actual water use in intercropped wheat and the expected water use in intercropped wheat, presented as:

$$\Delta \mathrm{WU}_{W} = \frac{P_{\mathrm{w}}\mathrm{WU}_{IW}}{\mathrm{PLER_w}\left(\mathrm{WU}_{\mathrm{SW,g}} + \mathrm{WU}_{SW,n}\right)} - 1 = \frac{P_{\mathrm{w}}\mathrm{WU}_{IW}}{P_{\mathrm{w}}\frac{Y_{\mathrm{IW}}}{\mathrm{Y_{SW}}}\left(\mathrm{WU}_{\mathrm{SW,g}} + \mathrm{WU}_{SW,n}\right)} - 1$$

$$= \frac{\mathrm{WU}_{IW}}{\frac{Y_{\mathrm{IW}}}{\mathrm{Y_{SW}}}\left(\mathrm{WU}_{\mathrm{SW,g}} + \mathrm{WU}_{SW,n}\right)} - 1$$

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where WU_{IW} based on land area of wheat in intercropping system, P_{w} is the ratio of the area of intercropped wheat.

ΔWU_M was used to evaluate the difference between the actual water use in intercropped maize and the expected water use in intercropped maize, presented as:

$$\Delta\mathrm{WU}_{M}=\frac{\mathrm{WU}_{IM}}{\frac{Y_{\mathrm{IM}}}{\mathrm{Y}_{\mathrm{SM}}}\left(\mathrm{WU}_{\mathrm{SM,g}}+\mathrm{WU}_{SM,n}\right)}-1 \quad (6)$$

where WU_{IM} based on land area of maize in intercropping system, P_{M} is the ratio of the area of intercropped maize.

$$\Delta\mathrm{WU}=\frac{\mathrm{WU}_{I}}{\mathrm{PLER_w}(\mathrm{WU}_{\mathrm{SW,g}}+\mathrm{WU}_{SW,n})+\mathrm{PLER_m}(\mathrm{WU}_{\mathrm{SM,g}}+\mathrm{WU}_{SM,n})}-1$$

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The change in water use efficiency by intercrops relative to that by sole crops, WUE, was calculated similarly as WU (Morris and Garrity, 1993):

$$\Delta\mathrm{WUE}=\frac{WUE_{I}}{P_{W}WUE_{SW}+P_{M}WUE_{SM}}-1$$

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where WUE_I, WUE_{SW}, and WEU_{SM} are water use efficiency of intercropping, sole wheat and sole maize (kg m^{-3}), respectively. A positive value in ΔWUE indicates that the intercropping system uses water more efficiently. For wheat and maize in intercropping, the ΔWUE was calculated as:

$$\Delta\mathrm{WUE}_{W}=\frac{\mathrm{WUE}_{IW}}{\mathrm{WUE}_{SW}}-1 \quad (9)$$

$$\Delta\mathrm{WUE}_{M}=\frac{\mathrm{WUE}_{IM}}{\mathrm{WUE}_{SM}}-1 \quad (10)$$

where WUE_{IW} and WUE_{IM} are water use efficiencies of intercropped wheat and intercropped maize (kg m^{-3}) based on land area of wheat or maize in the intercropping system, respectively.

In this study, calculations that did not consider water use during the non-growth period were defined as “before revision”, and calculations that did consider water use during the non-growth period were defined as “after revision”. A two-year experiment (described below) was conducted to test the effect of including non-growth period water use on WUE between the intercropping system and sole cropping.

Experimental site

The study was conducted at the Institute of Water Saving Agriculture in Arid Areas of China (34°18' N, 108°24' E and 506 m a.s.l.), which is located in Yangling, Shanxi Province, China. The climate at this location is classified as warm temperate and monsoon. The annual mean duration of sunshine is 2196 h y^{-1}, with a frost-free period of more than 210 days. The long-term (1959–2014) mean annual precipitation is 585 mm, of which 60–70% occurs primarily from July to September. The mean annual pan evaporation is approximately 993 mm yr^{-1} and the mean annual temperature is 12.9°C. According to the FAO/UNESCO soil classification system (FAO/UNESCO, 1993), the soil at the research site is a silty clay loam with a mean bulk density of 1.45 g cm^{-3}. Rainfall data were recorded using a standard weather station (Monitor Sensors, Caboolture QLD, Australia) located at the experimental site. The precipitation and air temperature data for the two experimental years are shown in Fig. 2.

Experimental design and field management

The experiment used a completely randomized design of three treatments replicated three times. The three treatments were sole wheat, sole maize, and wheat/maize relay strip intercropping. The intercropping plots were 3.5 m wide consisting of a 1.9-m wide maize strip (four rows of maize) and a 1.6-m wide wheat strip (eight rows of wheat) (Fig. 3). For each wheat/maize intercropped strip, 45.7% of the area was occupied by wheat and 54.3% by maize. Wheat and maize rows were oriented north-south. Each experimental plot area (for both the intercropped plots and sole crop plots) was 116 m^2 (10.5 × 11 m). A 1.5-m wide space was maintained between adjacent plots to minimize the effects of soil water migration. Row spacings in the sole crop plots were the same as in the intercropped plots. Wheat ('Xiaoyan 22') was planted in 20-cm rows at a rate of 180 kg seed ha^{-1} on 18 October 2014 and 9 October 2015. Maize ('Zhengdan 958') was planted in 50-cm rows at a density of 6.67 plants m^{-2} on 12 April 2015 and 15 April 2016. Maize plant spacing within a row was 30 cm for both intercrop and sole crop plantings. Wheat was harvested on 15 June 2013 and 15 June 2014, and maize was harvested on 22 August 2015 and 25 August 2016. Weeds and pests were controlled as required during each crop growing season. No irrigation was applied to the experimental area during the entire growing season for either the sole crop or intercropping systems in the two years.

For sole wheat and intercropped wheat, base fertilizer was applied at a rate of 150 kg N ha^{-1}, 180 kg P_2O_5 ha^{-1}, and 39 kg K_2O ha^{-1}. For sole maize and intercropped maize, fertilizer was applied at a rate of 235 kg N ha^{-1}, 180 kg P_2O_5 ha^{-1}, and 39 kg K_2O ha^{-1}, in which the full rate of P and K were applied as base fertilizer, and 50% of the nitrogen fertilizer was applied as base fertilizer and the remaining 50% was applied equally at the V6 (six leaves) and VT (tasseling) stages (Ritchie and Hanway, 1982). All base fertilizers were applied after plowing and leveling the experimental field and laying out the treatment plots.

Sampling and measurement method

Grain yield

Wheat grain yields were determined at maturity by harvesting all plants in a 3-m length of eight rows in each plot (4.8 m^2 sampling area). Maize grain yields were determined at maturity by harvesting all plants in a 3-m length of four rows in each plot (6-m^2 sampling area). Grain weight (t ha^{-1}) was determined after hand-threshing samples and was reported at 12% moisture content.

Soil water content

Soil water content was measured using Diviner 2000 capacitance probe (Sentek Pty Ltd., Australia). The measuring locations are shown in Fig. 3, and the detailed measurement method is described in Ma et al. (2019).

Soil water consumption

The directly measured evapotranspiration (ET_{sl}) was calculated as:

$$ET_{sl} = E_s + T + I$$

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where ET_{sl} is the ET measured by the direct measurement method, E_s (mm) is the soil evaporation measured using micro-lysimeters, T (mm) is the transpiration measured by sap flow meters, and I (mm) is the canopy interception.

Soil evaporation (Es, mm day^{-1}) was measured using micro-lysimeters (MLs) that were custom-made according to the specifications of Boast and Robertson (1982). Each micro-lysimeter consisted of two parts. One was the inner tank made from polyvinyl chloride (PVC) tubes, with a diameter of 11 cm and height of 20 cm. The other part was the outer tank made of galvanized iron, with an internal diameter of 12 cm and height of 20 cm.

Sap flow for wheat and maize were continuously measured to quantify transpiration using the Dynagage Flow32-1K system (Dynamax, Houston, TX, USA) based on the heat balance (Sakuratani, 1981). The sensors were installed strictly according to the manufacturer's instructions (Dynamax, 2007). Sap flow data were recorded averaged over 10-min intervals with a CR1000 data logger and two AM 16/32 multiplexers (Campbell Scientific, Logan, Utah). Sensor heat inputs were controlled by voltage regulators linked to the CR1000. The voltage was supplied by a power supply system consisting of solar panels and conventional car batteries.The measuring locations are shown in Fig. 3.It should be noted that this study was based on the accurate calculation of water migration, and further evaluated the water use and water use efficiency of each component crop in intercropping. Interested readers may learn more about the details in our previous study (Ma et al., 2020)

Land equivalent ratio (LER)

The advantage of intercropping was determined by calculating the land equivalent ratio (LER) (Mead and Willey, 1980).

$$\text{LER} = \text{PLER}_W + \text{PLER}_M = P_W \frac{Y_{IW}}{Y_{SW}} + P_M \frac{Y_{IM}}{Y_{SM}}$$

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where Y_{SW} and Y_{SM} are the wheat and maize grain yields in sole cropping (t ha^{-1}), respectively, Y_{IW} and Y_{IM} are the wheat and maize grain yields in intercropping based on land area of wheat or maize in intercropping system (t ha^{-1}), respectively; P_W and P_M are the planted proportion of wheat and maize in intercropping, respectively. LER > 1.0 indicates a land use advantage of intercropping expressed in terms of the relative land area required in both sole cropping systems to produce yields equivalent to an intercropping system.

Statistical analysis

Analysis of variance was performed using SPSS 21.0 (SPSS Inc., Chicago, IL, USA). Treatment means were compared based on the least significant difference (LSD) test ($p < 0.05$). The figures were drawn with Sufer v.8.0 (Golden Software Inc., Golden, CO), OriginPro 2016 (OriginLab Corporation, Northampton, MA, USA), and PowerPoint 2016 (Microsoft Corporation, Redmond, WA, USA).

Results

Grain yield and LER

Wheat yield differed significantly between the intercrop and sole crop systems ($p < 0.05$) in both years of the study. The intercropped wheat yield was 39.2% greater than sole wheat yield in 2015, and 32.9% greater in 2016 (Fig. 4A). The intercropped maize yield was 4.6% less than sole maize yield in 2015, and 7.0% less in 2016. The difference in grain yield between intercropped maize and sole maize was only significant in 2016 (Fig. 4B). The total yield for intercropping was 10.4% and 8.2% greater than the weighted means of sole cropping yield in 2015 and 2016, respectively (Fig. 4C). The LER for the intercropping system was 1.14 in 2015 (Fig. 4D), of which the partial LER (PLER) was 0.64 for wheat and 0.52 for maize. The LER for the intercropping system was 1.11 in 2016, of which the PLER was 0.61 for wheat and 0.50 for maize.

Soil water storage

The soil water storage for intercropped wheat (Fig. 5A and C) was lower than for sole wheat from about 125 days after planting (DAP) to 200 DAP in both years. The soil water storage for both sole wheat and intercropped wheat gradually decreased with time to wheat harvest, except at about 175 DAP in 2015 due to a large amount of rain. After wheat harvest, the soil water storage for intercropped wheat and sole wheat gradually increased, and the soil water storage for intercropped wheat was significantly greater than that of sole wheat in both years. Soil water storage for intercropped maize (Fig. 5B and D) was greater than for sole maize from 125 to 200 DAP. Soil water storage for sole maize was significantly greater for intercropped maize after 200 DAP, and the difference generally became larger with time.

Soil water distribution in intercropping

Overall, soil water content was higher in 2015 than in 2016 (Fig. 6). The soil water content distribution pattern was similar in the two years. During the wheat-only growing season in the intercropping system (April), the soil water content of the maize strip was greater than that of the area between the wheat and maize strips, and greater than that of the wheat strip. The soil water content was lower in 0–40 cm soil layer than in the soil layer below 40 cm. During the co-growth period for wheat and maize (May), the soil water content in the maize strip was lower than observed in April, but soil water was still greater for the maize strip than the wheat strip below 50 cm. The soil water content in the wheat strip was least in the 40–80 cm soil layer. After the wheat was harvested (July, maize-only growing season), the soil water content in the wheat strip began to recover, especially in 60–100 cm layer. The soil water content in the maize strip was lower, with the lowest moisture region concentrated at 0–40 cm.

Water use per species in the intercrop and sole crop systems

The growing season water use for both wheat and maize was higher with the intercropping system than for sole crops (Table 1). The growing season water use of intercropped wheat was 60 mm greater than that of sole wheat in 2015, and 57 mm greater in 2016. The growing season water use for intercropped maize was 22 mm greater than that of sole maize in 2015, and 30 mm greater in 2016. However, the non-growth period water use for the intercropping system was lower than the water used for both intercropped wheat and maize. The water use of sole wheat during the non-growth period was 37 mm greater than that of intercropped wheat in 2015, and 54 mm greater in 2016. The water use of sole maize during the non-growth period was 3 mm greater than that of intercropped maize in 2015, and 6 mm greater in 2016. Before revision of the water use period, intercropped wheat used 3.0% more water than sole wheat (2-year average), and the intercropped maize used 39.0% more water than sole maize. After revision of the water use period, intercropped wheat used 24.5% more water than sole wheat (2-year average), and intercropped maize used 11.0% more water than sole maize (Table 1).

Table 1 Water use (WU) for wheat and maize grown as sole crops or intercropped and during the non-growth period in 2015 and 2016 in Yangling, China.

Year	Treatments	WU (mm)		Total WU (mm)		ΔWU (%)	
		Growth period	Non-growth period	Before revision	After revision	Before revision	After revision
2015	Intercropped wheat	414	62	476	476	-3.4	-24.5
	Sole wheat	354	99	354	453		
	Intercropped maize	415	83	498	498	32.8	9.0
	Sole maize	393	86	393	479		
2016	Intercropped wheat	374	87	461	461	9.4	-24.3
	Sole wheat	317	141	317	458		
	Intercropped maize	400	98	498	498	44.7	13.0
	Sole maize	370	104	370	474		

Notes: The non-growth period refers to the period from wheat harvest to maize harvest for wheat, while it refers to the period from wheat sowing to maize sowing for maize. “Revision” refers to changing the water use calculation period to include the non-growth period.

3.5. WUE for intercrop and sole crop wheat and maize

Table 2 shows the comparison of WUE for wheat and maize before and after revision of the water use period. The WUE values for wheat and maize in the intercropping system were the same for before- and after-revision calculations. However, the WUE values for wheat and maize in the sole cropping system were higher calculated by the method before revision than after revision. Before revision, the WUE of intercropped wheat was 3.8% greater and 8.7% less than that of sole wheat in 2015 and 2016, respectively. After revision, the WUE of intercropped wheat was 32.7% and 32.1% greater than that of sole wheat in 2015 and 2016, respectively. Before revision, the WUE of intercropped maize was 25.1% and 30.9% less than that of sole maize in 2015 and 2016, respectively. After revision, the WUE of intercropped maize was 8.6% and 11.5% less than that of sole maize in 2015 and 2016, respectively (Table 2).

Table 2 Water use efficiency (WUE) for wheat and maize grown as sole crops or intercropped in 2015 and 2016 in Yangling, China. Before revision and after revision refer to the two calculation methods based on different water use periods described in the text.

Year	Treatments	WUE (Kg m^{-3})		ΔWUE (%)	
		Before revision	After revision	Before revision	After revision
2015	Intercropped wheat	1.74	1.74	3.8	32.7
	Sole wheat	1.68	1.31		
	Intercropped maize	1.82	1.82	-25.1	-8.6
	Sole maize	2.43	1.99		
2016	Intercropped wheat	1.73	1.73	-8.7	32.1
	Sole wheat	1.9	1.31		
	Intercropped maize	1.55	1.55	-30.9	-11.5
	Sole maize	2.25	1.75		

3.6. Advantage in water use and WUE in intercropping

The assessments of intercropping performance in terms of water use and water use efficiency were characterized using two indices: ΔWU and ΔWUE. If ΔWU < 0 or ΔWUE > 0, it indicated that intercropping could obtain a given yield with less water and higher water use efficiency than the sole crops. Before revision, the wheat/maize intercropping system consumed 13.8% more water in 2015 and 26.8% more water in 2016 than the expected water use based on the WUE and yields in sole cropping systems. After revision, the wheat/maize intercropping system consumed 9.0% less water in 2015 and 7.1% less water in 2016 than the expected water use (Table 3). Before revision, the WUE in the intercropping system was 15.1% less than the weighted means of sole crops in 2015, and 22.2% less in 2016. After revision, the WUE of the intercropping system was 5.6% greater than the weighted means of sole crops in 2015, and 4.9% greater in 2016 (Table 3).

Table 3 Differences in water use (ΔWU) and water use efficiency (ΔWUE) between the wheat/maize intercropping system and the sole crop system in 2015 and 2016 in Yangling, China. Positive values indicate that the intercropping values of WU or WUE were greater than the sole crop values. Before revision and after revision refer to the two calculation methods based on different water use periods described in the text.

Year	before revision		after revision	
	ΔWU (%)	ΔWUE (%)	ΔWU (%)	ΔWUE (%)
2015	13.8	-15.1	-9.0	5.6
2016	26.8	-22.2	-7.1	4.9

Discussion

5.1. Yield advantage

The main advantage of the intercropping system is increased yield compared with sole crop production (Agegnehu et al., 2008; Gao et al., 2014; Gou et al., 2017; Latati et al., 2016), which is advantageous to ensuring food security, and enhances economic benefits for farmers in poverty-stricken areas (Sharma et al., 2017). Several intercropping systems have been tested previously, such as wheat/mungbean (*Vigna radiata* L.) (Mandal et al., 1996), maize/soybean (*Glycine max* L.) (Du et al., 2018), wheat/soybean (Li et al., 2001b), maize/alfalfa (*Medicago sativa* L.) (Sun et al., 2018), wheat/cotton (*Gossypium hirsutum* L.) (Shah et al., 2016), and cereal/pea (*Pisum sativum* L.) (Monti et al., 2016). However, most intercropping studies have been conducted under irrigated conditions (Coll et al., 2012; Li et al., 2001a, b; Wang et al., 2015b). In this study, we found that the grain yield obtained with intercropping was greater than the grain yield from sole cropping, and the LER was above 1.0 in both years of the study (Fig. 4), indicating that wheat/maize intercropping indeed showed a yield advantage over sole crop production and improved the land use efficiency under rainfed conditions. As both population and food demand increase, the world faces enormous food security problems (Tscharntke et al., 2012; UN, 2017). These problems are intensified in China because of the strategy of fallow farming that has been proposed and gradually implemented. Therefore, the yield advantage we found for intercropping under rainfed conditions has great significance regarding land productivity for areas with similarly limited rainfall amounts, and in the context of fallow cultivation, relay intercropping may be a suitable production practice. Moreover, the magnitude of the yield advantage could be affected by rainfall amount, and it remains unclear as to what is the minimum rainfall where a yield advantage for intercropping would be observed. Determining this value will require further research on intercropping under different rainfall amounts.

5.2. Water use in wheat/maize intercropping

In arid and semi-arid areas, water shortage is the main limiting factor influencing crop growth and yields. Hence, efficient water utilization plays an important role in agricultural production (Daryanto et al., 2017; Gao et al., 2013; Zhao et al., 2014). There is, therefore, a need to evaluate the water use of intercropping under these conditions. Intercropping is a production system that efficiently uses resources, and there have been many related studies of water use in intercropping (Coll et al., 2012; Wang et al., 2015b). However, when comparing the water use in sole cropping systems to that in intercropping systems, there has always been a calculation problem, that is, the length of the calculation period for sole cropping was shorter than that for intercropping. The difference in the lengths of the calculation periods therefore probably results in overestimation of WUE for sole cropping and a diminishing of the perceived advantage of intercropping (Mao et al., 2012; Ren et al., 2019; Wang et al., 2015a). To more accurately evaluate water use of intercropping systems, the revised method not only considered water consumption during the non-growth period of the intercropping system, but also considered the water consumption during the non-growth period in the sole cropping system, making the length of the water consumption periods for sole cropping and intercropping consistent. In our study, before revision of the water use calculation period, the water use of the wheat/maize intercropping system in 2015 was greater than sole crop water use, but the WUE of the wheat/maize intercropping system was lower than the sole cropping system in both years. However, based on the revised method, we found that the wheat/maize intercropping system had lower water use and higher WUE than sole cropping in both years (Table 3), indicating that the intercropping system saved water compared with the sole cropping system in both years. This result confirmed our supposition that the previous calculation method underestimated the water-saving advantage of intercropping compared with sole cropping. This procedure more accurately assessed WUE for intercropping, and thereby provided a new understanding of whether intercropping saves water or not. Calculating water use and water use efficiency in this manner provides a good evaluation method for the design and management of intercropping systems.

To determine if the water saving advantage of intercropping was from the dominant crop or the subordinate crop, the water use and WUE of intercropped wheat and intercropped maize were also evaluated. Based on the revised calculation method, the WUE of intercropped wheat was greater than that of sole wheat, but the WUE of intercropped maize was slightly less than the WUE of sole maize (Table 2). This was because wheat was the more dominant crop than maize, and maize growth was inhibited during the early developmental stages due to limited water, with water deficit impacts on maize growth becoming more severe in later growth stages (Figs. 6 and 8). This was different than the result reported by Mao et al. (2012) for the maize/pea intercropping system in which the WUE of intercropped maize was increased while the WUE of field pea decreased. This was because maize was the dominant crop holding an advantage in maize/pea intercropping. This indicated that the water saving advantage of intercropping mainly came from the dominant wheat crop, consistent with the yield advantage attribution of intercropping. Furthermore, compared with the calculation method before revision, the water saving advantage of intercropped wheat was more significant and the water use disadvantage of the intercropped maize was reduced using the method after revision (Table 2).

5.3. Rainfall utilization and water use in the non-growth period

A large amount of water used in agriculture is lost by soil evaporation, which does not contribute to crop productivity (Kool et al., 2014; Wang et al., 2014). For example, 80% of the rainfall was found to be lost by soil evaporation in bare soil over the entire spring maize growth period in Gansu, China (Liu et al., 2014). Fallow decreases rainfall storage in soil due to soil evaporation (Nielsen and Vigil, 2017). Water consumption during the non-growth period is an important factor affecting WUE in intercropping and sole cropping systems. The results of this study showed that water consumption during the non-growth period was not negligible when assessing water use (Table 1). Comparing water consumption during the non-growth periods of both the intercropping and sole cropping systems, we found that water use with sole cropping was larger than that of intercropping in the non-growth period (Table 1). Replacing fallow with continuous cropping is an effective method for improving precipitation use efficiency (Nielsen et al., 2005; Nielsen et al., 2015). Similarly, intercropping has a longer period of vegetative ground cover and therefore inhibits the soil water loss from evaporation, especially during the period following wheat harvest. Large amounts of evaporative water loss occur during the non-growth period of sole crops because the soil surface is completely exposed to the atmosphere. This indicated that intercropping can preserve soil moisture and accumulate rainwater in the soil to be used by plants.

In our study, the wheat/maize intercropping system consumed 8.1% (average of two years) less water to produce the same yield as the sole cropping system (Table 3). This finding indicated that intercropping did not put pressure on the use of soil water for sustainable production in this region. Therefore, intercropping used soil water efficiently during the growing season, and maintained rainwater during the non-growth period, resulting in spatially and temporally efficient use of soil water. With the potential future reduction of land resources and soil quality degradation, the strategy of fallow farming has been proposed and gradually implemented. In some regions of the North China Plain, previous studies have shown that the use of fallow following the conventional double-cropping system could ease the pressure on water resources and restore the groundwater level, but result in a 13% drop in annual grain yield (Xiao et al., 2017). Intercropping is probably a good choice when high yields need to be guaranteed and soil productivity improved. Especially in areas where water resources are limiting factors for agricultural production, improving the efficiency of rainwater capture and use is crucial for maximizing food production. Additionally, because intercropping results in staggered growing seasons and a prolonged growth period, the soil surface is covered with crops for a longer period, thereby providing significant ecological benefits resulting from reduced soil erosion by wind.

Based on the results of the water use evaluation of the intercropping system, we found that rainfall during the non-growth period is an important source of SWS, which better preserves water and is conducive to crop growth in the next growing season. Further study will be needed to understand how to make better use of this period to maximize precipitation storage. Additionally, further study will be required to make recommendations regarding crop combinations, planting densities, and row spacings for intercropping systems that will further improve and optimize water consumption and water use efficiency.

Conclusion

A modification of intercropping water use assessment performed in this study promoted an objective evaluation of intercropping water consumption compared with sole cropping. Such an evaluation and assessment is extremely important in areas with limited water resources. In this study, the water consumption and water use efficiency of the two individual crop components of the intercropping system were accurately calculated. The results provide a foundation for further optimization and configuration of the intercropping system. Wheat/maize intercropping increased the total grain yield and improved the land use efficiency. The improved method for calculating water use considered the additional water use that occurred during the non-growth period of sole cropping, making the length of the water use calculation period consistent with that of intercropping. Water use during the non-growth period of sole cropping was greater than water use during the non-growth period of intercropping. Therefore, this part of the total water use in sole cropping should not be neglected when comparing water use of intercropping with water use of sole cropping. Through the improved method, we found that intercropping increased wheat WUE compared with sole cropping, but decreased maize WUE. WUE of intercropping system was greater than sole crop WUE in both years. This result indicated that the method of calculating WUE before revision underestimated the water use advantage of intercropping.

Declarations

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Figures

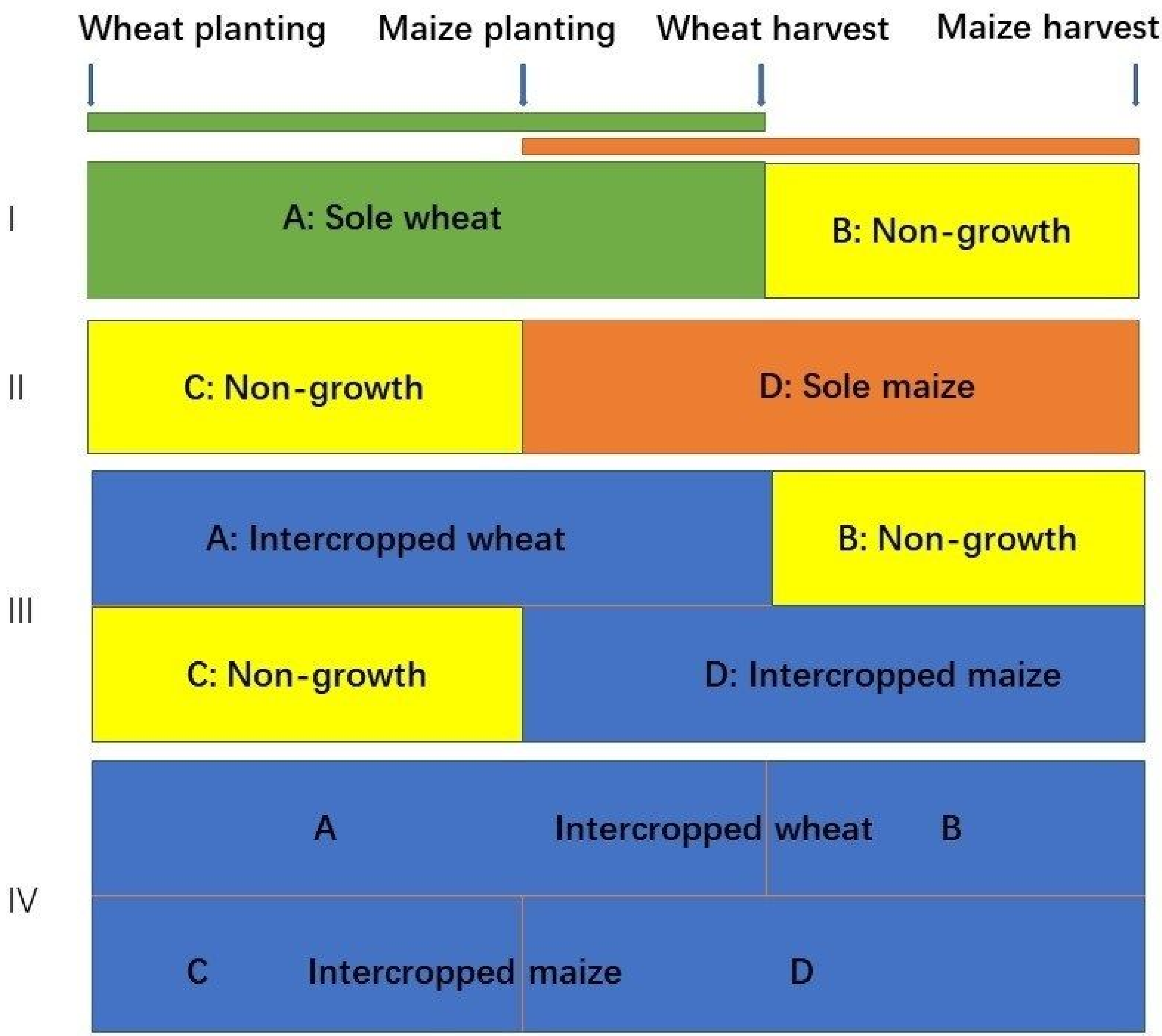

Figure 1

Diagrammatic representation of the timing of planting and harvest for wheat and maize in sole cropping and intercropping systems. A, B, C, and D represent four different periods for water use in sole cropping and intercropping systems. I, II, III, and IV represent sole wheat, sole maize, wheat/maize intercropping (not include the non-growth period) and wheat/maize intercropping.

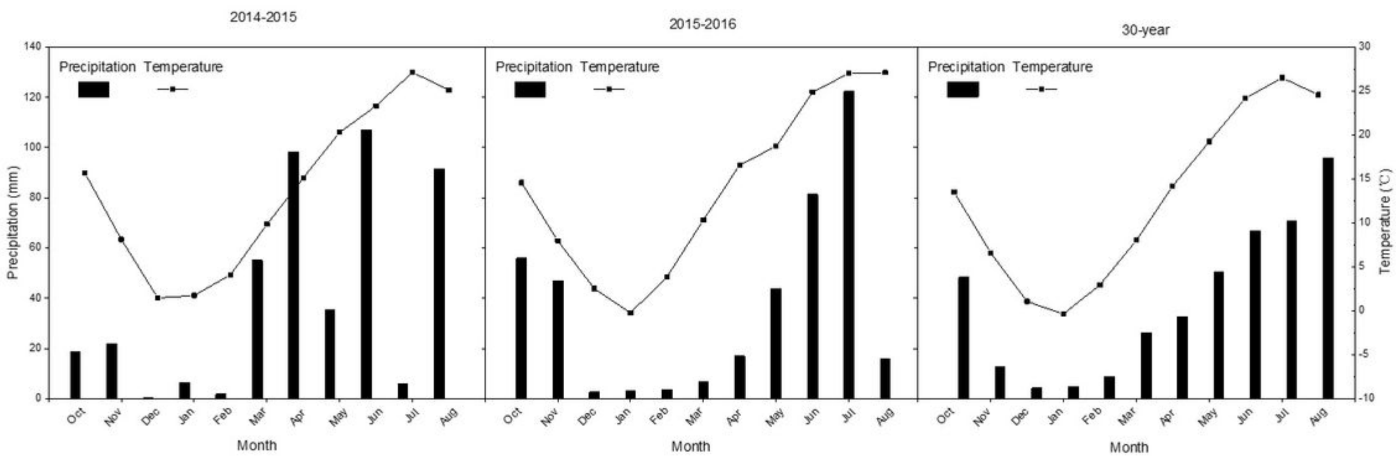

Figure 2

Monthly precipitation and temperature for the 2014–2015 and 2015–2016 wheat/maize growing seasons and the 30- year average at the experimental site near Yangling, China

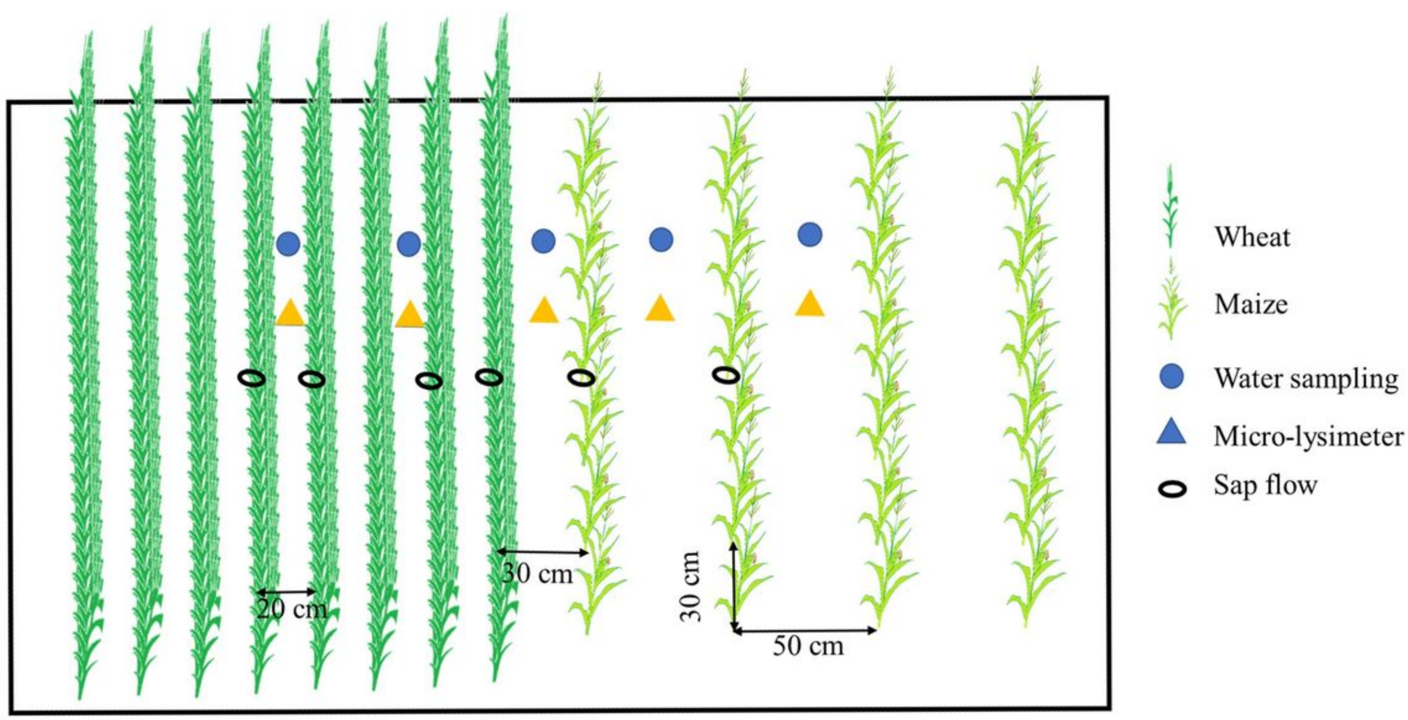

Figure 3

Arrangement of soil water sampling, evaporation (micro-lysimeter), and transpiration (sap flow) measurement sites relative to wheat and maize rows in the intercrop plot.

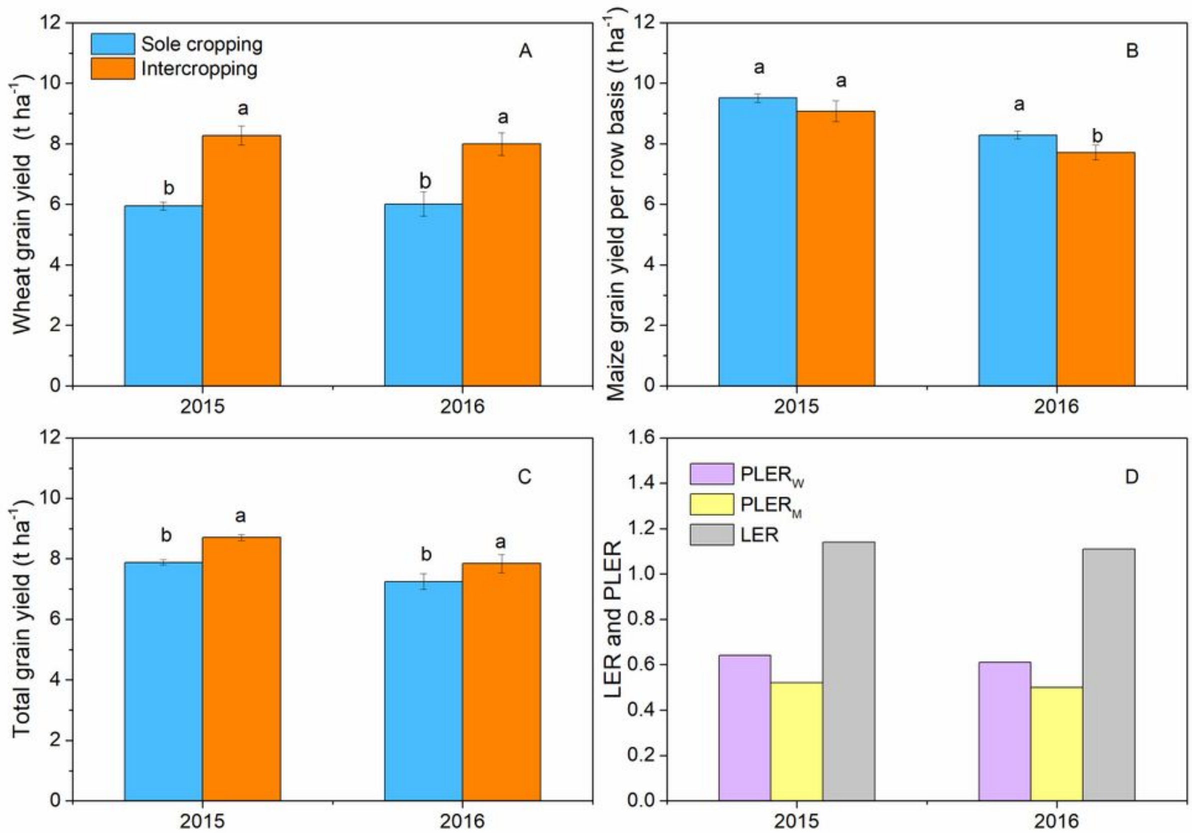

Figure 4

Grain yield in different cropping systems, and land equivalent ratio (LER) and partial LER (PLER) near Yangling, China in 2015 and 2016. The values for the intercropped wheat and maize are on an equivalent basis of comparable land area of the sole crops. The total grain yields of intercropping and sole cropping are the sum of the yields produced by two component crops based on their proportions in the intercropping. Different letters above bars in a group indicate statistically significant differences as tested by LSD (0.05). The error bar is the standard error of three replicates.

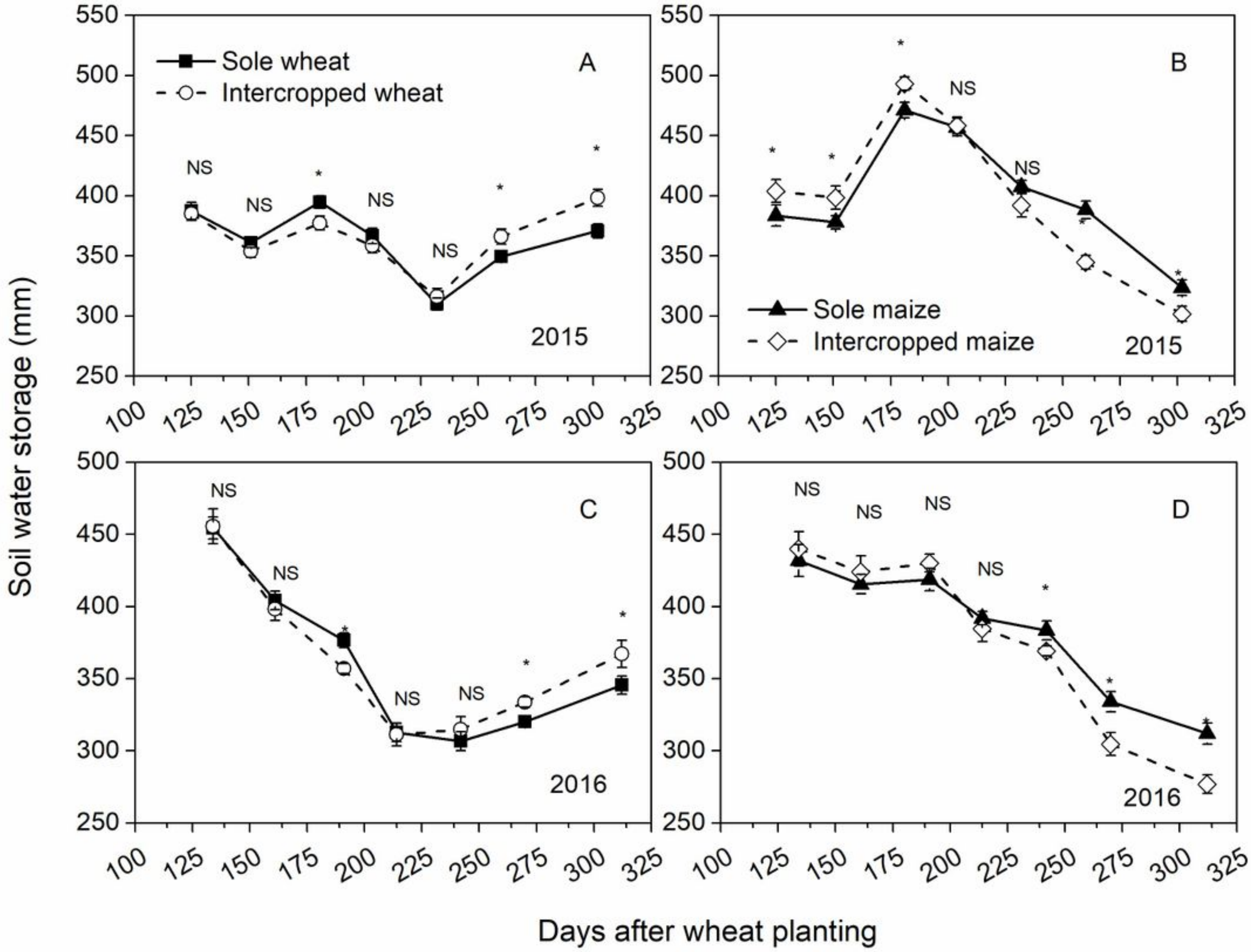

Figure 5

Soil water storage in the 0–160 cm soil layer for intercrops and sole crops at Yangling, China. A=2015 wheat; B=2015 maize; C=2016 wheat; D=2016 maize. * indicates significance at P=0.05. NS indicates a non-significant difference. The error bar is the standard error of three replicates.

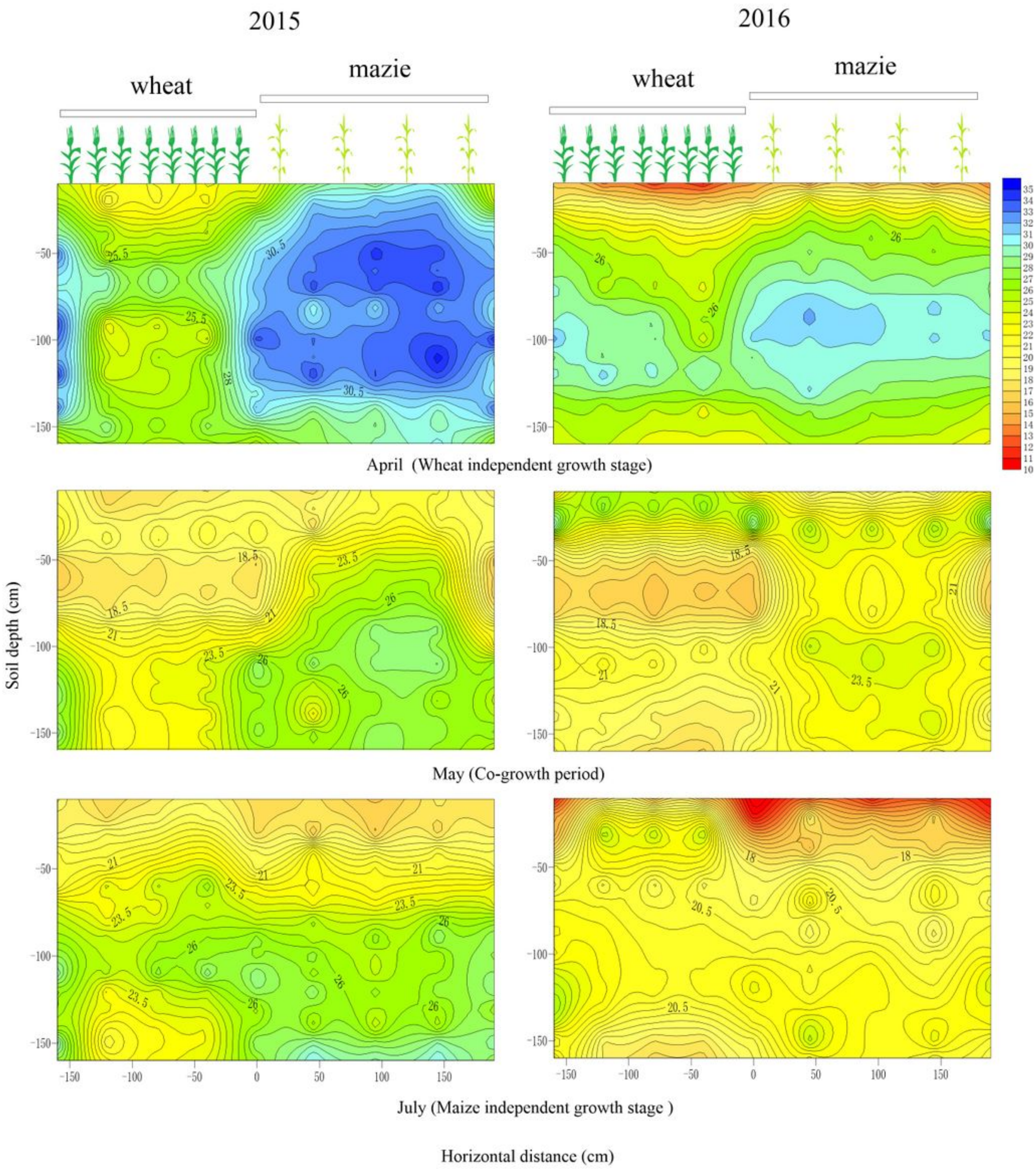

Figure 6

Spatial distribution of soil water storage (mm) in intercrop plots at different horizontal distances from the center of the plot at three growth stages in 2015 and 2016 in Yangling, China. Numbers on the isolines indicate mm of soil water storage.