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Yield benefits from replacing chemical fertilizers with manure under water deficient conditions of the winter wheat – summer maize system in the North China Plain

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ABSTRACT

Recycling of livestock manure in agroecosystems has been shown to improve crop yields, increase resource use efficiency, and reduce adverse environmental consequences from intensive crop-livestock systems. However, such effects have not been well explored for the widely planted winter wheat - summer maize double cropping system in the North China Plain, especially under deficit irrigation. A three years split-plot field experiment was established with and without irrigation (at wheat jointing stage) as main plots, and with chemical fertilizer N (Fc), manure N (Fm), and 50 % chemical fertilizer N + 50 % manure N (Fc + m) using the same amount of N input as sub-plots. Irrigation increased wheat yield significantly by 8–19 % in the normal years (2015/2016 and 2016/2017, $p < 0.05$) and 124 % in the dry year (2017/2018, $p < 0.01$), which was attributed to the higher spike number and aboveground biomass. Specifically, irrigation increased aboveground biomass before ($p < 0.01$) and after anthesis ($p = 0.08$), as well as the fruiting efficiency (grain number per spike weight at anthesis, $p < 0.01$) and grain number per unit area ($p < 0.01$), resulting in increased wheat grain yield. However, irrigation in the wheat season reduced maize yield significantly ($p < 0.05$) by 5 % in the normal years. The maize yield of Fc+m was 7 % higher than that of Fc under irrigated conditions ($p < 0.05$). Overall, manure application alone had a higher annual yield without irrigation, while mixed fertilization yielded better and earned more (both were 6% higher than Fc) with irrigation. In conclusion, the annual yield of the winter wheat - summer maize system can be maintained or even increased by replacing mineral N with manure, suggesting multiple benefits from integrating manure application into cereal-based cropping systems.

1. Introduction

Agriculture faces multiple challenges to sustain food security for a growing global population by increasing crop yield with lower environmental costs through enhancing the sustainability of agricultural production (Chen et al., 2014a; Godfray et al., 2010; Mortada et al., 2018). The North China Plain produces about two-thirds of the total wheat and more than one-quarter of total maize in China, and it is thus a key region for the national food supply (Lu and Fan, 2013). Winter wheat - summer maize double cropping is the main cropping system in this region. Excessive irrigation and fertilization schemes have been adopted in wheat and maize production since the 1980s (Xiao et al., 2019), leading to severe resource and environmental consequences, such as air pollution (Liu et al., 2013; Rosas et al., 2015), NO_3 leaching (Zhang et al., 2015), soil acidification (Guo et al., 2010), and groundwater depletion (Zheng et al., 2010). In addition, overuse of mineral fertilizer and irrigation have contributed to the depletion of groundwater resource and its quality with long-term impacts on food security (Chen et al., 2014a; Zhang et al., 2015). Changing these trends requires alternative fertilization and irrigation strategies to maintain crop yield and reduce the environmental costs towards a more sustainable crop production system in the North China Plain (Wang et al., 2014; Ying et al., 2017).

Although the total nitrogen (N) in animal manure from livestock production exceeds N used from chemical fertilization globally (Bouwman et al., 2009), a large proportion of manure N is lost to the

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environment through gaseous and leaching losses (Galloway et al., 2010). The total annual production of manure ranges from 2800 to 3600 Mt in China (Wang et al., 2010; Chadwick et al., 2015), which contains 14–20 Mt N (Ma et al., 2010; Chadwick et al., 2015). However, nearly 20–45 % of manure in China is unmanaged and thus mostly lost to the environment, with a high risk of exacerbating the already serious environmental issues (Chadwick et al., 2015). Therefore, better integration of animal manure in the cropping system can effectively reduce N losses and lower the need for mineral N fertilizer (Bouwman et al., 2013), which helps to maintain or enhance crop production with lower environmental impacts.

Replacing chemical N with efficient use of manure is one of the important ways to reduce the environmental emissions from the animal production system and decrease chemical N application in the crop production system. A global review on the substitution of chemical fertilizer N with livestock manure showed that the crop yield and N uptake increased by 4.4 % and 7.8 %, respectively (Xia et al., 2017). Additionally, the manure amendment can be a practical solution to reduce the negative effect of water stress under water-saving conditions (Afshar et al., 2014; Ali et al., 2018). Many studies have investigated the effect of replacing chemical fertilizer N with manure on crop yield (Xia et al., 2017), while few studies have focused on its impact under water deficit (Wang et al., 2017), especially for major grain crops with a perspective on productivity at the cropping system level.

Thus, we aimed 1) to evaluate the yield and yield stability of winter wheat and summer maize with different irrigation and fertilization regimes; 2) to quantify the yield effects of substituting chemical fertilizer N with manure under water stress in winter wheat, and verify the legacy effect of water management in winter wheat on the yield of subsequent maize; and 3) to understand how yield components may explain the yield response to irrigation and fertilization regimes.

2. Materials and methods

2.1. Study sites

A field experiment was carried out from October 2015 to October 2018 at the Wuqiao Experimental Station of China Agricultural University (37°41′N, 116°36′E), in Cangzhou City, Hebei. This region has a typical sub-humid continental monsoon climate with cold winter and hot summer. The annual active accumulated temperature ($\geq$ 0 °C) is 4 826 °C and the annual frost-free period is 201 days (Zhang et al., 2019; Zhao et al., 2019a). The long-term average annual rainfall is 562 mm, with a sharp yearly fluctuation and erratic seasonal distribution (Wang et al., 2018). The annual precipitation was 667, 455, and 701 mm for the wheat-maize rotation system in 2015 − 2016, 2016 − 2017, and 2017 − 2018, respectively, and only one-quarter happened during the winter wheat growing season (Fig. 1). The soil at the experimental site is loamy Mollisol developed on an alluvial plain. Basic characteristics of the 0 − 20 cm soil layer were as follows: soil organic carbon (SOC) 9.0 g kg^{-1}, total nitrogen (TN) 1.3 g kg^{-1}, total phosphorus (TP) 1.73 g kg^{-1}, available phosphorous (Olsen-P) 89.8 mg kg^{-1}, and soil pH (H_2O) 7.74.

2.2. Experimental design and set-up

The experiment was conducted to investigate the yield performance of winter wheat (*Triticum aestivum* L.) and summer maize (*Zea mays* L.) under different irrigation and fertilization conditions within a winter wheat - summer maize cropping system. The experiment was arranged as a split-spot design with three replicates, and the plot size was 100 m^2 (10 m × 10 m). The main plots were two water regimes: irrigation once at the jointing stage of winter wheat (90 mm; W1) and no irrigation during the whole wheat growing season (W0). There was a 2-m buffer to separate the two water regimes. All treatments received a volume of 90 mm irrigation before wheat sowing to ensure seed germination. Plots were irrigated evenly using surface irrigation with a 4-inch plastic-coated hose. A flow meter was installed near the outlet of the hose to record the water used. Similar irrigation was applied to any of the water treatments for the summer maize to investigate the residual effect of water deficit from previous wheat to subsequent maize. Specifically, no irrigation was applied in the 2016 and 2018 maize seasons, while they were irrigated once (90 mm) to ensure seed germination in the 2017 maize season due to little rainfall before and after sowing. The sub-plots were three fertilization treatments: Fc, 100 % chemical fertilizer N; Fc + m, 50 % chemical fertilizer N + 50 % manure N, and Fm, 100 % manure N. The winter wheat variety was Jimai 22 and summer maize variety were Zhengdan 958 for all the three years.

Treatment Fc was fertilized with 157.5 kg N ha^{-1}, 60.3 kg P ha^{-1}, and 93.4 kg K ha^{-1} for winter wheat, and 178.5 kg N ha^{-1}, 45.2 kg P ha^{-1}, and 93.4 kg K ha^{-1} for summer maize (Table S1). The chemical fertilizers were applied in the form of urea, diammonium phosphate, and potassium sulfate. The livestock manure was retrieved as slurry directly from a beef cattle house nearly four weeks before application to the field. The amounts of chemical fertilizers and manure for Fc + m and Fm were determined by the water and nutrient content of the manure (Table S2) to match the same total application rate of N, P, and K with Fc. The same amount of applied N may lead to higher K content with manure, especially for Fm (Table S1). Superphosphate was also used to match the same amount of P across treatments. Rotary tillage with residue incorporation was performed for winter wheat and no-till with residue mulching was done for summer maize. All the manure and chemical fertilizers were surface broadcast as basal fertilizer for winter wheat before rotary tillage (15-cm depth). For summer maize, 100 % of manure, chemical fertilizer P, chemical fertilizer K, and 26 % of chemical fertilizer N were applied at the trefoil stage after ditching (15-cm depth and 10-cm width) in the middle of plant rows, and the rest of chemical fertilizer N (74 %) was fertilized as topdressing at flare opening stage before rainfall (Table S1). Winter wheat was sown with 15-cm row spacing. Summer maize was sown with 60-cm row spacing and 24-cm plant distance in a row. The amounts of seed and irrigation water, and the date of sowing and harvest are shown in Table S3.

2.3. Sampling and analytical procedures

2.3.1. Yield, aboveground biomass, harvest index, and yield components

Grain yield, aboveground biomass, and harvest index were measured from an area of 2 m^2 (2 sites × 1 m in width × 1 m in length) and 7.2 m^2 (2 sites × 1.2 m in width × 3 m in length) for winter wheat and summer maize, respectively, in the middle of each plot at maturity. Specifically, plants were cut at the ground level and air-dried until they reached a constant weight. Then, all the plant samples were separated into grains and residues, and aboveground biomass and grain yield (air-dried) were measured. Harvest index is the ratio of grain yield to aboveground biomass at maturity and calculated as:

Harvest index = Grain yield / Aboveground biomass (1)

For winter wheat, the spike number per hectare was counted in two 1-m^2 sites, grain number per spike was determined by counting the grains of each spike from 40 randomly selected plants in each plot before harvest. For summer maize, the ear density was counted in two 3.6-m^2 frames, kernel number per ear was measured on 20 randomly selected ears from each plot. The 1000-grain/kernel weight of wheat/maize was measured by weighing 1000 seeds/kernels from yield measurement sample with 6 replicates. These sub-samples were oven-dried at 75 ℃ for 72 h to achieve constant dry weight, and the calculated water content of grains (air-dried) was used to transfer the grain yield to dry weight.

The effect size has been defined as the difference between two treatments—experimental and control (Osenberg et al., 1997; Zhao et al., 2019b), and it was used to compare annual yield under manure N (Fc + m and Fm) versus chemical fertilizer N (Fc). The effect size of manure fertilizer was calculated as the natural logarithm of the

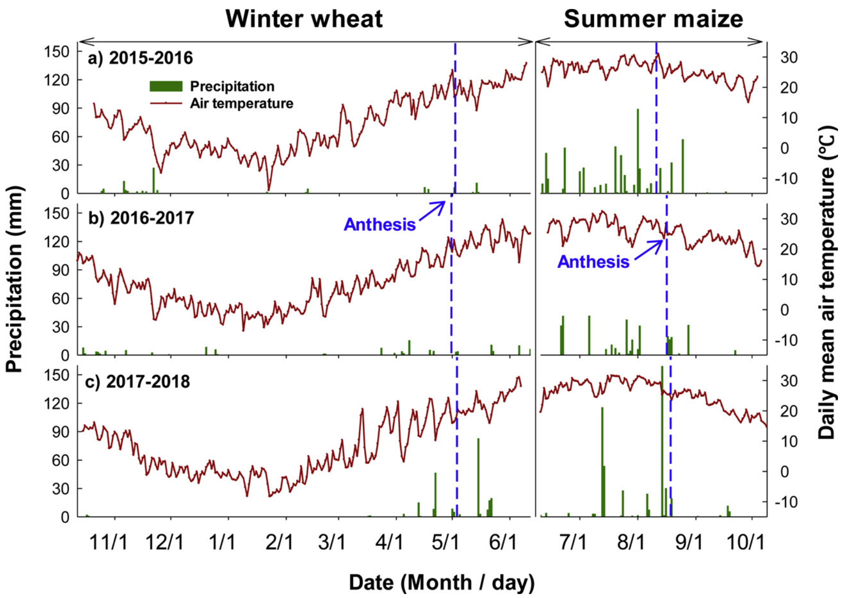

Fig. 1. Daily precipitation (green vertical bars) and mean air temperature (red solid curve) during the winter wheat and summer maize growing seasons for a) 2015-2016, b) 2016-2017 and c) 2017-2018. The blue dotted lines indicated the date of anthesis for winter wheat and summer maize. (For interpretation of the references to colour in the Figure, the reader is referred to the web version of this article).

response ratio (Hedges et al., 1999):

Effect size = ln (Ym / Yc) (2)

Where Ym is the wheat-maize system yield of Fc + m and Fm, and Yc is the yield of Fc.

2.3.2. Dry matter accumulation

The aboveground parts from 0.30 m^2 for winter wheat and 0.43 m^2 for summer maize in each plot were sampled at regular intervals to measure dry matter accumulation. Plant samples were oven-dried at 75 °C for 72 h to achieve constant dry weight.

The post-anthesis dry matter accumulation was calculated as the difference between dry matter content of the aerial plant part at physiological maturity and that at anthesis:

Dry matter accumulation during post-anthesis = Dry matter at maturity – Dry matter at anthesis (3)

The contribution of dry matter accumulation during post-anthesis to grain yield was calculated from the ratio of dry matter accumulation during post-anthesis to grain yield at maturity.

Contribution ratio (%) = Dry matter accumulation during post-anthesis / Grain yield (4)

2.3.3. Fruiting efficiency and spike portioning index

Fruiting efficiency (grains g^{-1}) was calculated as (Slafer et al., 2015):

Fruiting efficiency = Grain number / Spike dry weight at anthesis (5)

Spike partitioning index was calculated as (Foulkes et al., 2011):

Spike partitioning index = Spike dry weight at anthesis / Dry matter accumulation at anthesis (6)

2.3.4. Economic analysis

Economic analysis was conducted to determine the economic benefits of winter wheat-summer maize system through replacing chemical fertilizer N with manure under water deficient condition. The total expenses were calculated based on local conditions, including fertilizers, electricity (used for irrigation), machinery, pesticide, seeds, and labor. Gross income was estimated according to the current price and yield. Net income was obtained by deducting the total cost from the gross income.

2.4. Statistical analyses

Statistical analyses were carried out using the Data Processing System (DPS) software version 7.05 (Tang and Zhang, 2013). Significant differences between the N fertilization treatments under different water regimes were tested by two-way analysis of variance (ANOVA) in combination with Fisher's Least Significant Difference (LSD) test at a significance level of $p < 0.05$. Three-way ANOVA was used when considering the years. Residuals were checked for normality and homogeneity by Shapiro and Leneve's tests, respectively. The Pearson's correlation coefficients between grain yield and other parameters were calculated using SPSS version 21.0 (IBM SPSS Software Inc., Armonk, NY, USA), and were shown as heatmap made by the Heatmap illustrator (Deng et al., 2014). Other figures were potted with SigmaPlot version 14.0 (Systat Software Inc., San Jose, CA, USA).

3. Results

3.1. Grain yield

Wheat yield was significantly influenced by year ($p < 0.001$), water regime ($p < 0.001$), and their interaction ($p < 0.001$) (Table 1). Wheat yield in the 2017/2018 season was 44–47 % lower than those in the normal seasons (2015/2016 and 2016/2017) (Fig. 2) due to the low and erratic distribution of precipitation (Fig. 1), especially for the trials without irrigation. Irrigation increased wheat grain yields by 19 %, 8%, and 124 % in the 2015/2016, 2016/2017, and 2017/2018 seasons compared to unirrigated treatments (Fig. 2a, b, and c), respectively.

Maize yield was influenced by year ($p < 0.05$) and the interaction of year and water regime ($p < 0.01$) (Table 1). The average grain yield of maize in the 2018 season was 7% and 12 % higher than those in the 2016 and 2017 seasons ($p < 0.05$), respectively. Irrigation in the wheat season reduced maize yield averagely by 5% in the 2016 and 2017 seasons (normal years for wheat), but increased maize yield by 7% in the 2018 season (dry year for wheat) compared to unirrigated treatments (Fig. 2d, e, and f, $p < 0.05$). Remarkably, the response of maize yield to irrigation showed an opposite trend compared to that of wheat. This was also confirmed by a negative correlation between the yield of wheat and maize (Fig. 3c, $p < 0.01$), regardless of irrigation and fertilization.

Taken together, the variation in annual yield of winter wheat - summer maize system mainly relied on winter wheat yield, as supported by the positive correlation between annual yield and wheat yield (Fig. 3a, $p < 0.001$). The annual yield of wheat and maize in Fm was comparable to that in Fc, and was 6–7 % higher than that of Fc+m

Table 1
Combined analysis of variances for grain yield, agronomical and physiological traits of winter wheat, summer maize, and annual grain yield in the three years.

Traits	Source of variation						
	Year (Y)	Water (W)	Fertilizer (F)	Y × W	Y × F	W × F	Y × W×F
Winter wheat							
Yield	***	***	ns	***	ns	ns	ns
Spike number	**	***	*	**	ns	*	ns
Grain number	*	*	*	*	ns	ns	ns
1000-grain weight	***	ns	ns	**	ns	ns	*
Aboveground biomass	***	***	ns	***	ns	ns	ns
Harvest index	**	***	ns	**	ns	ns	ns
DMa[a]	***	**	*	***	ns	ns	ns
DMpa[b]	*	ns	ns	*	ns	ns	ns
CR[c]	*	ns	ns	*	ns	ns	ns
Fruiting efficiency	**	**	ns	ns	ns	ns	ns
Spike partitioning index	**	***	ns	ns	ns	*	ns
Summer maize							
Yield	*	ns	ns	**	ns	ns	ns
Ear number	**	ns	ns	*	ns	ns	ns
Kernel number	***	ns	ns	ns	*	*	ns
1000-kernel weight	ns	*	ns	ns	ns	ns	ns
Aboveground biomass	**	ns	ns	*	ns	ns	ns
Harvest index	**	ns	ns	ns	ns	ns	ns
DMa	**	ns	ns	ns	ns	ns	ns
DMpa	***	ns	ns	ns	ns	ns	ns
CR	***	ns	ns	ns	ns	ns	ns
Wheat-maize system							
Yield	*	***	ns	***	ns	**	ns

*$p < 0.05$, ** $p < 0.01$, *** $p < 0.001$, and ns means not significant difference.
[a] DMa, dry matter accumulation at anthesis.
[b] DMpa, dry matter accumulation during post-anthesis.
[c] CR, contribution ratio of DMpa to grain yield.

without irrigation in the normal seasons (2015/2016 and 2016/2017, $p < 0.05$). However, the annual yield of wheat and maize in Fc + m under irrigation was 5–6 %, on average, higher than those in Fm and Fc over the three seasons (Fig. S1, $p < 0.05$). Thus, these results indicate that the recommended fertilization strategy without irrigation was 100 % manure fertilization, while the 50 % chemical fertilizer N and 50 % manure combination benefited for annual yield under irrigation (Figs. 4 and S1).

3.2. Yield components

3.2.1. The yield components of winter wheat (Spike number, grain number, and 1000-grain weight)

The number of spikes positively correlated with grain yield, regardless of irrigation, fertilization, and year (Fig. 5, $p < 0.01$), indicating that spike number was the main yield component determining wheat yield. Similar to yield, the number of spikes in the 2017/2018 season was 29 % and 35 % lower than those in the 2015/2016 and 2016/2017 seasons (Table 2, $p < 0.01$), respectively. Irrigation increased the number of spikes by 11 %, 11 %, and 55 % in the 2015/2016, 2016/2017, and 2017/2018 seasons (Table 2, $p < 0.05$), respectively. The wheat spike number in Fm was 10 % higher than that in Fc in the 2015/2016 season ($p < 0.05$) without irrigation. In addition, mixed fertilization increased the spikes number by 17–20 % than manure application alone in the 2016/2017 and 2017/2018 seasons under irrigated condition (Table 2, $p < 0.01$).

The grain number was positively correlated with grain yield without irrigation (Fig. 5, $p < 0.01$). The grain number of wheat in Fm was 10 % higher than in Fc + m in the 2015/2016 season (Table 2, $p < 0.05$) without irrigation. The 1000-grain weight was positively correlated with grain yield in the 2017/2018 season (Fig. 5, $p < 0.01$), and was increased by 13 % due to irrigation (Table 2, $p < 0.05$).

3.2.2. The yield components of summer maize (Ear number, Kernel number, and 1000-kernel weight)

Maize yield was positively correlated with the number of ears (Fig. 5), demonstrating the importance of ear number in determining maize yield. The ear number in the 2018 season was 8% higher than that in the 2016 season (Table 3, $p < 0.01$). Irrigation in winter wheat season reduced the 1000-kernel weight of summer maize by 2% on average among the three seasons, compared to unirrigated treatments

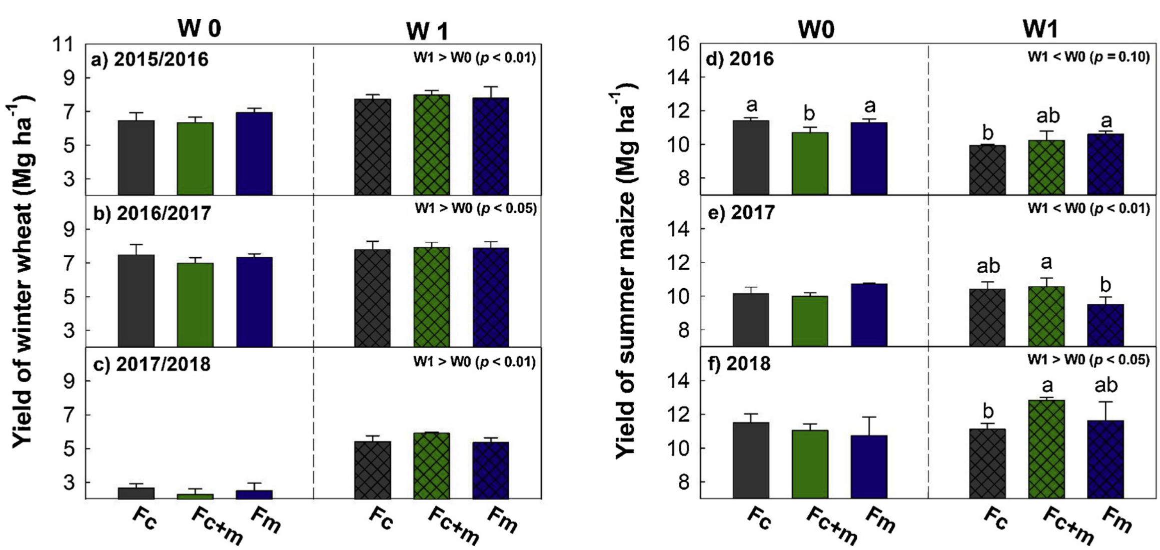

Fig. 2. The yield (oven-dried) of winter wheat (a, b, c) and summer maize (d, e, f) under chemical fertilizer N (Fc), 50 % chemical fertilizer N + 50 % manure N (Fc + m), and manure N (Fm) with (W1) or without irrigation (W0) in the three years. The yields of winter wheat and summer maize in treatments W0 and W1 of each growing season were pair-compared and the results are shown in the top right corner. Different lowercase letters within the column under the same water management mean significant differences at $p < 0.05$ by Fisher's Least Significant Difference (LSD) test. Values are means ± standard errors ($n = 3$).

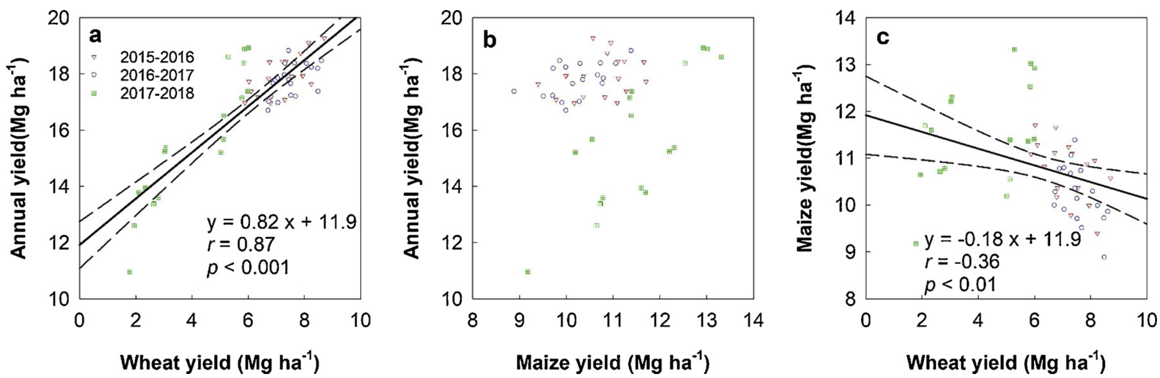

Fig. 3. The relationships between winter wheat yield and annual yield (a), summer maize yield and annual yield (b), and winter wheat yield and summer maize yield (c) in 2015-2016 (red triangle), 2016-2017 (blue circle) and 2017-2018 (green square) growing seasons. The solid line and medium dash lines indicate the regression line and 95 % confidence intervals. No linear relationship was observed between summer maize yield and annual yield. (For interpretation of the references to colour in the Figure, the reader is referred to the web version of this article).

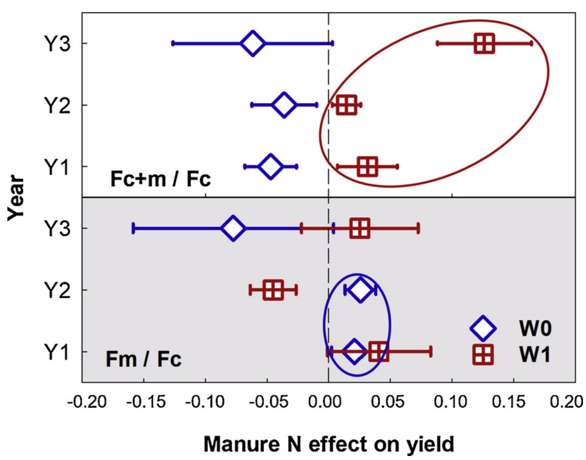

Fig. 4. The effect sizes on annual yield (wheat + maize) under Fc + m (50 % chemical fertilizer N + 50 % manure N, white filled) and Fm (manure N only, gray filled) versus Fc (chemical fertilizer N, as CK) with (W1) or without irrigation (W0) in 2015-2016 (Y1), 2016-2017 (Y2) and 2017-2018 (Y3). Values are means ± standard errors (n = 3).

(Table 1 and 3, $p < 0.05$).

3.3. Aboveground biomass and harvest index

3.3.1. Winter wheat

The aboveground biomass at maturity and harvest index of wheat were affected by year ($p < 0.01$), water regime ($p < 0.001$), and their interaction ($p < 0.01$) (Table 1). The aboveground biomass in the 2016/2017 season was 19.5 Mg ha^{-1}, and was 21 % and 107 % higher than those in the 2015/2016 and 2017/2018 seasons ($p < 0.01$), respectively. The highest harvest index was found in the 2015/2016 season (0.44), which was 7% and 15 % higher than those in the 2017/2018 and 2016/2017 seasons (Table 2, $p < 0.05$), respectively. The aboveground biomass positively correlated with grain yield regardless of irrigation and fertilization (Fig. 5, $p < 0.01$). Irrigation increased aboveground biomass and harvest index by 4–94 % and 5–16 %, respectively, compared to the unirrigated treatments, varying greatly with seasonal precipitation and weather conditions in the three years (Table 2).

3.3.2. Summer maize

The aboveground biomass of maize in the 2016 and 2017 seasons were 26 % and 20 % higher than that in the 2018 season (Table 3, $p < 0.01$), respectively. The grain yield of maize was negatively correlated with aboveground biomass, while positively correlated with harvest index (Fig. 5). Thus, lower aboveground biomass and higher harvest index contributed to the higher maize yield.

3.4. Post-anthesis dry matter accumulation and its contribution to grain yield

3.4.1. Winter wheat

Irrigation increased the dry matter accumulation of wheat before and after anthesis (Table 4 and Fig. S2). Dry matter accumulation during post-anthesis was positively correlated with grain yield (Fig. 5, $p < 0.05$). However, dry matter accumulation at anthesis correlated positively with grain yield only under unirrigated condition.

3.4.2. Summer maize

For summer maize, the dry matter accumulation before and after anthesis, as well as the contribution ratio of dry matter accumulation during post-anthesis to grain yield were year dependent (Table 1 and Fig. S3, $p < 0.01$). The grain yield of maize was negatively correlated with both the dry matter accumulation during post-anthesis and its contribution ratio to grain yield, regardless of irrigation and fertilization (Fig. 5, $p < 0.05$).

3.5. Fruiting efficiency and spike partitioning index (winter wheat)

Fruiting efficiency was positively correlated with wheat yield (Fig. 5, $p < 0.05$), and influenced by year ($p < 0.01$) and water regime ($p < 0.01$) (Table 1). The fruiting efficiency in the 2017/2018 season was 58 % and 43 % lower than those in the 2015/2016 and 2016/2017 seasons ($p < 0.05$, Table 4), respectively. Irrigation at the jointing stage of wheat increased fruiting efficiency by 37 %, on average, in all fertilization treatments over the three years (Table 4, $p < 0.01$).

Spike partitioning index was negatively correlated with grain yield (Fig. 5, $p < 0.05$), and was influenced by year ($p < 0.01$), water regime ($p < 0.001$), and their interaction ($p < 0.05$) (Table 1). The lowest spike partitioning index was detected in the 2016/2017 season, and was ~40 % lower than those in the 2015/2016 and 2017/2018 seasons (Table 4, $p < 0.01$). Irrigation once after sowing decreased spike partitioning index by 15 % on average (Table 4, $p < 0.01$).

3.6. Economic analyses

The annual cost of machinery, pesticide, and seeds was similar between different irrigation and fertilization treatments (Table 5), due to identical field managements (Table S5). The annual net income without irrigation was 24 411—27 165 ¥ ha^{-1}, once more irrigation increased net income by 15 % on average for the three years. Compared with chemical fertilization, manure had higher costs due to higher inputs of

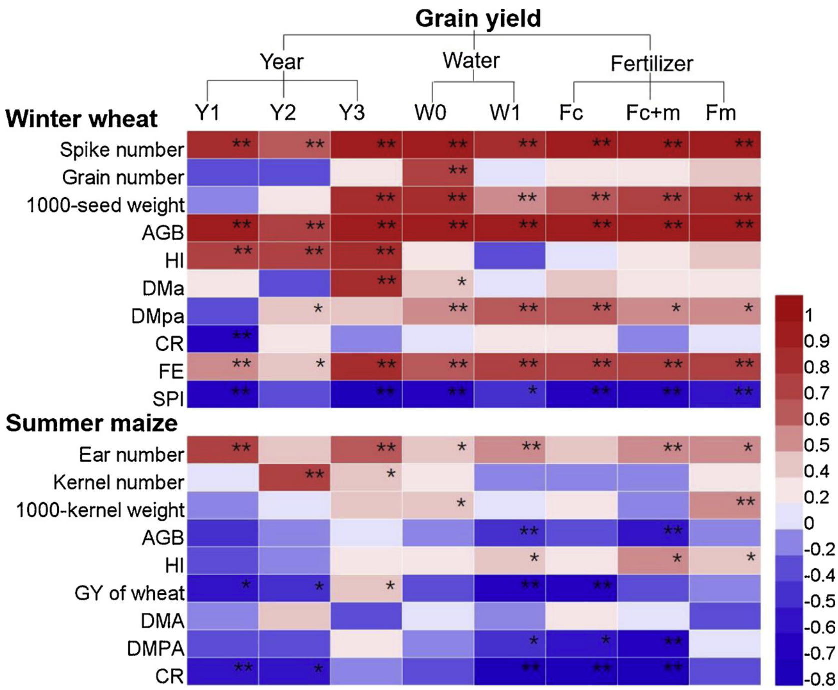

Fig. 5. Heatmap of Pearson's correlation coefficients between grain yield and yield components and other parameters for winter wheat and summer maize. Spike number, Grain number, 1000-grain weight, Aboveground biomass (AGB), Harvest index (HI), Dry matter accumulation at anthesis (DMa), Dry matter accumulation during post-anthesis (DMpa), Contribution ratio of DMpa to grain yield (CR), Fruiting efficiency (FE) and Spike partitioning index (SPI) were used for winter wheat analysis, and Ear number, Kernel number, 1000-kernel weight, AGB, HI, Previous wheat grain yield (GY of wheat), DMa, DMpa, and CR were used for summer maize analysis.

Table 2
Yield components, aboveground biomass, and harvest index of winter wheat under chemical fertilizer N (Fc), 50 % chemical fertilizer N + 50 % manure N (Fc + m), and manure N (Fm) with (W1) or without irrigation (W0) in the three years.

Treatments		Spike number (m^{-2})	Grain number ($spike^{-1}$)	1000-seed weight (g)	Aboveground biomass (Mg ha^{-1})	Harvest index
2015/2016						
W0	Fc	680 ± 35 b	36.3 ± 1.3 ab	39.4 ± 1.1 b	14.78 ± 0.90 a	0.44 ± 0.02 a
	Fc + m	751 ± 30 a	35.1 ± 2.0 b	40.8 ± 0.2 a	14.78 ± 0.68 a	0.43 ± 0.00 a
	Fm	752 ± 23 a	38.7 ± 1.9 a	41.3 ± 1.1 a	15.91 ± 0.57 a	0.44 ± 0.00 a
W1	Fc	799 ± 6 a	31.0 ± 1.3 a	39.5 ± 0.6 a	17.48 ± 0.38 a	0.44 ± 0.01 b
	Fc + m	827 ± 8 a	30.6 ± 1.3 a	38.4 ± 0.8 a	17.61 ± 0.17 a	0.45 ± 0.01 ab
	Fm	808 ± 24 a	32.5 ± 1.3 a	39.0 ± 1.1 a	16.66 ± 1.16 a	0.47 ± 0.01 a
2016/2017						
W0	Fc	820 ± 24 a	36.7 ± 1.4 a	36.7 ± 0.7 a	19.79 ± 0.41 a	0.38 ± 0.03 a
	Fc + m	797 ± 33 a	36.6 ± 1.8 a	36.7 ± 0.9 a	18.89 ± 0.38 a	0.37 ± 0.01 a
	Fm	759 ± 65 a	36.7 ± 2.6 a	37.5 ± 1.0 a	18.90 ± 0.52 a	0.39 ± 0.01 a
W1	Fc	888 ± 52 ab	32.8 ± 1.1 a	35.8 ± 0.3 b	19.90 ± 1.36 a	0.39 ± 0.01 a
	Fc + m	947 ± 14 a	34.2 ± 1.5 a	36.0 ± 1.0 ab	20.14 ± 0.69 a	0.39 ± 0.00 a
	Fm	810 ± 48 b	35.4 ± 1.6 a	38.3 ± 1.0 a	19.60 ± 0.67 a	0.40 ± 0.00 a
2017/2018						
W0	Fc	426 ± 29 a	30.8 ± 1.7 a	33.4 ± 1.9 a	6.80 ± 0.33 a	0.39 ± 0.03 a
	Fc + m	414 ± 29 a	29.8 ± 1.1 a	30.4 ± 1.3 b	5.90 ± 0.79 a	0.39 ± 0.03 a
	Fm	445 ± 57 a	30.6 ± 3.1 a	31.0 ± 1.3 ab	6.56 ± 1.02 a	0.38 ± 0.01 a
W1	Fc	664 ± 28 ab	31.9 ± 0.7 ab	34.8 ± 1.1 a	12.09 ± 0.70 a	0.45 ± 0.01 a
	Fc + m	725 ± 10 a	30.4 ± 2.1 b	36.5 ± 0.4 a	13.02 ± 0.13 a	0.45 ± 0.00 a
	Fm	603 ± 61 b	35.1 ± 0.4 a	36.1 ± 0.9 a	12.21 ± 0.79 a	0.44 ± 0.01 a

Different lowercase letters within a column of the same water regime in each year mean significant differences at $p < 0.05$ by Fisher's Least Significant Difference (LSD) test. Values are means ± standard errors ($n = 3$).

manure fertilizer and labor, which led to 9% lower net income without irrigation and 7% lower net income with irrigation. Although mixed fertilization required more labor to transport and broadcast the manure and chemical fertilizer, it had higher yields and gross incomes with irrigation. Therefore, chemical fertilization had a higher net income without irrigation (¥ 27 165 ha^{-1}) and mixed fertilization earned more with irrigation (¥ 31 107 ha^{-1}).

4. Discussion

4.1. Crop yield response to water and nitrogen management

Our results indicate that replacement of 100 % of chemical fertilizer N by manure could maintain annual crop yield under no irrigation condition, while 50 % replacement can produce a higher yield of maize with irrigation. Without irrigation, water is the most limiting factor for crop growth and yield, rather than N (Albrizio et al., 2010; Olesen et al., 2000). However, the increase of crop yields was largely attributed to enhanced N uptake of crops with irrigation (Edmeades, 2003), which was supported by the positive correlation between crop yield and N

Table 3
Yield components, aboveground biomass, and harvest index of summer maize under chemical fertilizer N (Fc), 50 % chemical fertilizer N + 50 % manure N (Fc + m), and manure N (Fm) with (W1) or without irrigation (W0) in the three years.

Treatments		Ear number (m^{-2})	Kernel number (ear^{-1})	1000-kernel weight (g)	Aboveground biomass (Mg ha^{-1})	Harvest index
2016						
W0[#]	Fc	6.44 ± 0.15 a	617 ± 13 a	308 ± 4 b	22.2 ± 2.4 a	0.52 ± 0.01 a
	Fc + m	6.44 ± 0.25 a	572 ± 13 b	316 ± 8 a	24.2 ± 0.1 a	0.51 ± 0.02 a
	Fm	6.67 ± 0.35 a	592 ± 20 ab	307 ± 2 b	23.0 ± 1.8 a	0.54 ± 0.02 a
W1	Fc	5.93 ± 0.40 a	589 ± 14 a	312 ± 2 a	24.8 ± 0.1 a	0.54 ± 0.00 a
	Fc + m	6.06 ± 0.30 a	601 ± 2 a	310 ± 5 a	25.0 ± 0.7 a	0.53 ± 0.02 a
	Fm	6.44 ± 0.20 a	576 ± 9 a	308 ± 4 a	24.1 ± 0.9 a	0.53 ± 0.02 a
2017						
W0	Fc	6.67 ± 0.31 a	513 ± 4 a	308 ± 3 b	22.9 ± 1.1 a	0.50 ± 0.01 a
	Fc + m	6.50 ± 0.12 a	499 ± 5 a	315 ± 1 a	22.3 ± 1.0 a	0.51 ± 0.01 a
	Fm	6.83 ± 0.24 a	518 ± 17 a	308 ± 4 b	22.3 ± 1.8 a	0.50 ± 0.03 a
W1	Fc	7.11 ± 0.07 a	496 ± 14 a	306 ± 3 a	23.7 ± 1.9 a	0.48 ± 0.03 a
	Fc + m	7.00 ± 0.12 a	512 ± 10 a	302 ± 4 a	23.8 ± 2.0 a	0.48 ± 0.02 a
	Fm	6.75 ± 0.06 a	489 ± 16 a	302 ± 4 a	22.1 ± 2.0 a	0.50 ± 0.01 a
2018						
W0	Fc	7.08 ± 0.10 a	472 ± 5 a	317 ± 12 a	20.9 ± 0.9 a	0.55 ± 0.01 ab
	Fc + m	6.25 ± 0.20 b	497 ± 25 a	321 ± 5 a	18.7 ± 0.7 a	0.52 ± 0.03 b
	Fm	6.62 ± 0.30 ab	501 ± 4 a	304 ± 21 a	18.7 ± 1.3 a	0.56 ± 0.01 a
W1	Fc	6.71 ± 0.06 a	485 ± 27 b	306 ± 5 a	18.7 ± 1.3 a	0.53 ± 0.02 a
	Fc + m	7.18 ± 0.30 a	529 ± 9 a	308 ± 5 a	19.3 ± 2.3 a	0.55 ± 0.01 a
	Fm	7.04 ± 0.30 a	497 ± 10 ab	301 ± 10 a	17.5 ± 0.2 a	0.56 ± 0.01 a

[#] Same irrigation was applied in summer maize, W1 and W0 mean with and without irrigation in the wheat season, respectively. Different lowercase letters within a column of the same water regime in each year mean significant differences at $p < 0.05$ by Fisher's Least Significant Difference (LSD) test. Values are means ± standard errors ($n = 3$).

yield (Fig. S4a). Manure N requires time to be mineralized before being available for crop uptake (Chen et al., 2014b; Zhou et al., 2016), which was also confirmed by the insufficient N supply, lower grain yield, and dry matter accumulation with 100 % manure fertilization. Long-term (13 years) application of feedlot manure to cropland increased soil pH and salinity (Miller et al., 2016), which could offset the positive effects of greater organic matter from manure. This was commonly attributed to the long storage period of manure (Pedersen et al., 2020). However, manure substitutions (Fc + m and Fm) had little effects on soil pH and C/N ratio in our study (Table S6), which mainly due to the short-term field experiment and manure storage. The avail-P contents of soils before and after the three-year experiment exceeded the agronomic threshold of 60 mg kg^{-1} (Howard, 2006), which indicated higher rates of P fertilization, and the yields of all treatments were not limited by P supply. Therefore, the mixed fertilization (chemical fertilizer N and manure N) can act as N sources for both early (from chemical fertilizer N) and late (from manure N) N uptake, increase soil N and C content, and maintain soil pH and C/N ratio, which contributed to higher annual

Table 4
Dry matter accumulation at anthesis (DMa), during post-anthesis (DMpa), the contribution ratio of DMpa to grain yield (CR), fruiting efficiency (FE), and spike partitioning index (SPI) of winter wheat and DMa, DMpa, and CR of summer maize under chemical fertilizer N (Fc), 50 % chemical fertilizer N + 50 % manure N (Fc + m), and manure N (Fm) with (W1) or without irrigation (W0) in the three years.

Treatments		Winter wheat					Summer maize		
		DMa (Mg ha^{-1})	DMpa (Mg ha^{-1})	CR (%)	FE (grains g^{-1})	SPI	DMa (Mg ha^{-1})	DMpa (Mg ha^{-1})	CR (%)
2015 – 2016									
W0	Fc	5.82 ± 0.51 a	10.16 ± 1.32 a	159 ± 26 a	139 ± 24 a	0.21 ± 0.01 b	11.3 ± 0.5 a	10.8 ± 2.1 a	95 ± 19 a
	Fc + m	4.24 ± 0.53 b	9.24 ± 1.70 a	147 ± 29 a	161 ± 20 a	0.23 ± 0.01 a	11.6 ± 1.3 a	12.6 ± 1.3 a	118 ± 16 a
	Fm	4.41 ± 0.30 b	10.93 ± 1.29 a	158 ± 21 a	170 ± 10 a	0.23 ± 0.01 a	10.2 ± 1.1 a	12.8 ± 2.9 a	114 ± 26 a
W1	Fc	5.98 ± 0.95 a	8.42 ± 1.89 ab	110 ± 28 ab	178 ± 31 a	0.19 ± 0.01 a	11.4 ± 0.5 a	13.4 ± 0.6 a	135 ± 5 a
	Fc + m	5.88 ± 0.47 a	7.39 ± 1.65 b	94 ± 24 b	185 ± 14 a	0.19 ± 0.00 a	10.6 ± 0.8 a	14.4 ± 0.2 a	141 ± 6 a
	Fm	5.61 ± 0.39 a	9.92 ± 0.41 a	128 ± 6 a	185 ± 19 a	0.19 ± 0.01 a	10.6 ± 0.6 a	13.4 ± 1.4 a	127 ± 13 a
2016 – 2017									
W0	Fc	15.26 ± 0.67 a	4.46 ± 2.15 a	59 ± 29 a	94 ± 5 a	0.14 ± 0.01 a	9.5 ± 1.1 a	13.4 ± 1.2 a	133 ± 17 a
	Fc + m	14.24 ± 0.91 b	3.40 ± 0.71 a	49 ± 12 a	95 ± 2 a	0.14 ± 0.01 a	9.1 ± 1.1 a	13.2 ± 0.8 a	132 ± 10 a
	Fm	14.02 ± 1.26 b	4.98 ± 2.52 a	68 ± 35 a	97 ± 12 a	0.15 ± 0.01 a	10.0 ± 0.9 a	12.4 ± 1.3 a	115 ± 12 a
W1	Fc	13.99 ± 1.17 a	7.63 ± 2.75 a	96 ± 29 a	144 ± 7 a	0.11 ± 0.01 a	9.8 ± 0.5 a	13.8 ± 1.6 a	132 ± 11 a
	Fc + m	13.87 ± 0.73 a	6.88 ± 1.32 a	87 ± 16 a	157 ± 44 a	0.11 ± 0.03 a	10.1 ± 1 a	13.7 ± 2.7 a	131 ± 30 a
	Fm	12.36 ± 1.17 a	6.25 ± 2.31 a	80 ± 32 a	169 ± 25 a	0.10 ± 0.02 a	10.2 ± 0.9 a	11.9 ± 1.5 a	126 ± 19 a
2017 – 2018									
W0	Fc	6.44 ± 0.45 a	1.15 ± 1.52 a	38 ± 50 a	58 ± 7 a	0.22 ± 0.01 b	10.0 ± 0.4 a	10.8 ± 1.3 a	95 ± 14 a
	Fc + m	6.47 ± 0.21 a	2.10 ± 0.62 a	91 ± 24 a	50 ± 10 a	0.24 ± 0.01 a	10.1 ± 0.7 a	8.6 ± 0.8 a	78 ± 6 a
	Fm	5.55 ± 0.77 a	2.57 ± 1.42 a	101 ± 51 a	65 ± 18 a	0.24 ± 0.01 a	10.7 ± 1.4 a	8.0 ± 2.6 a	74 ± 22 a
W1	Fc	8.58 ± 0.26 b	3.99 ± 1.01 a	75 ± 22 a	87 ± 5 a	0.21 ± 0.01 a	10.9 ± 1.5 a	7.8 ± 0.8 a	70 ± 7 a
	Fc + m	10.18 ± 0.48 a	2.49 ± 1.02 a	42 ± 17 a	83 ± 5 a	0.19 ± 0.01 a	9.8 ± 0.2 ab	9.5 ± 2.2 a	74 ± 17 a
	Fm	8.68 ± 0.84 b	3.84 ± 0.99 a	71 ± 18 a	85 ± 4 a	0.20 ± 0.01 a	7.8 ± 0.8 b	9.7 ± 0.8 a	85 ± 11 a

Different lowercase letters within a column of the same water regime in each year mean significant differences at $p < 0.05$ by Fisher's Least Significant Difference (LSD) test. Values are means ± standard errors ($n = 3$).

Table 5
Average income and cost of winter wheat-summer maize system under chemical fertilizer N (Fc), 50 % chemical fertilizer N + 50 % manure N (Fc + m), and manure N (Fm) with (W1) and without irrigation (W0) in the three years.

Item	W0			W1		
	Fc	Fc + m	Fm	Fc	Fc + m	Fm
Annual costs (¥ ha^{-1})						
Fertilizers						
Urea	1 313	555	0	1 313	555	0
Diammonium phosphate	1 575	1 099	0	1 575	1 099	0
Potassium sulfate	1 350	63	0	1 350	63	0
Superphosphate	0	0	517	0	0	517
Manure	0	2 272	4 542	0	2 272	4 542
Electricity (for irrigation)	660	660	660	1 155	1 155	1 155
Machinery	4 800	4 800	4 800	4 800	4 800	4 800
Pesticide	450	450	450	450	450	450
Seeds	2 930	2 930	2 930	2 930	2 930	2 930
Labor	700	1 750	2 200	1 000	2 050	2 500
Total	13 778	14 578	16 099	14 573	15 373	16 894
Gross income (¥ ha^{-1})	40 942	38 989	40 891	44 007	46 480	44 345
Net income (¥ ha^{-1})	27 165	24 411	24 792	29 435	31 107	27 451

The total expenses were calculated based on local conditions, including fertilizers, electricity (used for irrigation), machinery, pesticide, seeds, and labor. Gross income was estimated according to the current price and yield. Net income was obtained by deducting the total cost from the gross income. The unit price and total amount of all cost and income in the present study were attached in detail as Table S1 and S5 in supporting information.

crop yield with irrigation.

4.2. The legacy effect of irrigation on maize yield

Maize yield was negatively correlated with wheat yield in the double cropping system. Firstly, the competitive use of soil N by the previous wheat will restrict the N supply for the subsequent maize, especially under high wheat yield conditions with chemical N fertilization. These results were confirmed by the negative correlation of N yield between wheat and maize in 2015 – 2016 and 2016 – 2017 (Fig. S4b), especially under chemical N fertilization. Maize yield was negatively correlated with wheat yield under mineral N fertilization; however, this relationship was not observed under manure replacement. Given that the N release from manure is much slower than mineral N, which could contribute to the N supply of the subsequent crop due to the very short interval between wheat and maize in the double cropping system (Fang et al., 2006; Heggenstaller et al., 2008; Liu et al., 2018). Secondly, the utilization of residual N and water by wheat from the maize season also contributed to the negative correlations, which was supported by the negative correlation of water consumption between wheat and maize (Fig. S4c). Thirdly, a large amount of manure applied in the wheat season was not mineralized due to lower soil water content (De Neve and Hofman, 2002), which might be used by the subsequent maize under higher temperature and soil moisture conditions (Guntiñas et al., 2012). Therefore, the negative relationship between the yield of wheat and maize was mainly attributed to the competition for soil water and nitrogen.

4.3. Grain yield and agronomical traits

The response of annual yield of double cropping system to irrigation and substitution of mineral fertilizer with manure was determined by wheat under water-saving conditions, where rainfall primarily restricted crop water supply during the winter wheat season (Zhao et al., 2018). Spike number was the main determinant of wheat yield in this study, although other affecting factors (e.g. grain number and 1000-grain weight) was observed in previous studies under water deficit condition (Slafer et al., 2014; Xue et al., 2006, 2014). In general, spike number is more sensitive to inadequate water supply, especially at or before the jointing stage (Meena et al., 2019), while grain number and 1000-grain weight were strongly cultivar-dependent (Abdoli and Saeidi, 2012; Li et al., 2016). Thus, the wheat yield was mainly determined by spike number and affected by water supply.

Under water-limited conditions, the lower yield was due to the reductions in both aboveground biomass and harvest index, and aboveground biomass contributed more to yield decrease compared to harvest index (Olesen et al., 2000; Thapa et al., 2019). Crop water deficit at the critical growth stages (e.g. jointing, anthesis, and grain filling) affects dry matter accumulation differently before and after anthesis (Blum, 2009; Fischer, 2011; Li et al., 2010; Thapa et al., 2019), which subsequently reduced grain yield (Shi et al., 2016; Li et al., 2018). The dry matter at anthesis was the determining factor for grain number per unit area (Foulkes et al., 2011), which was confirmed by a positive correlation between the dry matter accumulation at anthesis and spike number/grain number (Table S4, $p < 0.05$). Dry matter accumulation after anthesis and biomass remobilization are two main sources of grain yield (Xue et al., 2006; Ercoli et al., 2008), and higher dry matter accumulation during post-anthesis improved harvest index and grain yield (Wang et al., 2016).

This study confirmed that the fruiting efficiency is an important trait for high yield associated with grain number per unit area under water-saving conditions. Previous findings suggest that increased spike partitioning index is not associated with a trade-off with fruiting efficiency, nor a trade-off between spike partitioning index and grain yield (Foulkes et al., 2011; Gaju et al., 2014; Ferrante et al., 2015; Xu et al., 2018). However, an increased spike partitioning index was associated with the decreases in both fruiting efficiency (Table S4) and grain yield for a large spike phenotype (i.e., Jimai 22 in the present study) (Gaju et al., 2009). The spike partitioning index was negatively correlated with grain number per unit area, aboveground biomass at anthesis and maturity (Table S4), indicating that lower dry matter accumulation at anthesis may lead to higher spike partitioning index.

This study implies that the dry matter accumulation (before and after anthesis) and spike number are two main controlling factors for wheat yield under water-saving conditions. Therefore, field management strategies for increasing biomass and spike number would have great potential to increase crop yield with limited irrigation. Such strategies include introducing newer drought-tolerant cultivars with higher biomass (Xue et al., 2014), and precision planting that increases spike number (Zhao et al., 2013). Higher biomass under low limited irrigation may be obtained by deeper rooting that extract water from deeper soil layers (Thapa et al., 2017). Strategies should also focus on reducing excess transpiration, e.g. by better managing the size of the crop canopy through fertilization management, and here the use of manure N may also be considered as positive field practices. Higher spike numbers may be achieved by lower soil evaporation and higher leaf transpiration through increasing leaf area index, decreasing photosynthetically active radiation penetration ratio, and increasing canopy humidity (Zhao et al., 2013). Improved knowledge of yield-increasing mechanisms could promote the development of combined field management strategies to cope with the serious water shortage problems in the North China Plain. Improved integration with the use of manure in such cropping systems could have the additional benefit of reducing the serious environmental pollution problems from livestock waste.

5. Conclusions

Three years of field study confirmed that it is feasible to increase annual yield in winter wheat - summer maize double cropping system under water-saving conditions through replacing chemical fertilizer N with manure. Manure fertilization alone was a better strategy for obtaining higher annual grain yields without irrigation, while mixed chemical fertilizer N and manure had higher annual grain yields with irrigation. The changes in annual yield of the double cropping system were mainly determined by the yield of wheat rather than maize, which was due to the limited water supply in the wheat season. Irrigation increased wheat yield by 8–19 % in the normal years and 124 % in the dry year. Specifically, irrigation increased dry matter accumulation before and after anthesis, as well as the fruiting efficiency (grain number per spike weight at anthesis) and grain number per unit area, resulting in increased wheat grain yield. A negative correlation was observed between wheat and maize yield, indicating that there were seasonal competition and complementarity effects within the two crops for water and nitrogen. Irrigation in wheat season decreased maize yield by 5% in the normal years, while increased by 7 % in the dry year. During the three seasons, the maize yield of mixed fertilization (Fc + m) was 7 % higher, on average, than that of Fc with irrigation. In conclusion, the replacement of chemical N with manure provides a better fertilization strategy to maintain or even increase annual grain yield and net income, which has great potentials for improving the sustainability of crop production in the North China Plain.

CRediT authorship contribution statement

Xiquan Wang: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Writing - original draft. **Yadong Yang:** Conceptualization, Formal analysis, Funding acquisition, Project administration, Resources. **Jie Zhao:** Conceptualization, Formal analysis, Investigation, Methodology, Software, Supervision. **Jiangwen Nie:** Data curation, Investigation, Methodology, Validation, Visualization. **Huadong Zang:** Data curation, Funding acquisition, Project administration, Resources, Software, Supervision, Validation, Visualization. **Zhaohai Zeng:** Funding acquisition, Project administration, Resources. **Jørgen Eivind Olesen:** Software, Supervision, Validation, Visualization, Writing - review & editing.

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Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:https://doi.org/10.1016/j.eja.2020.126118.

References

Abdoli, M., Saeidi, M., 2012. Effects of water deficiency stress during seed growth on yield and its components, germination and seedling growth parameters of some wheat cultivars. Int. J. Agric. Crop Sci. 4, 1110–1118.
Afshar, R.K., Chaichi, M.R., Assareh, M.H., Hashemi, M., Liaghat, A., 2014. Interactive effect of deficit irrigation and soil organic amendments on seed yield and flavonolignan production of milk thistle (*Silybum marianum* L. Gaertn.). Ind. Crops Prod. 58, 166–172.
Albrizio, R., Todorovic, M., Matic, T., Stellacci, A.M., 2010. Comparing the interactive effects of water and nitrogen on durum wheat and barley grown in a Mediterranean environment. Field Crops Res. 115, 179–190.
Ali, S., Jan, A., Manzoor, Sohail, Khan, A., Khan, A., Inamullah, M.I., Zhang, J., Daur, I., 2018. Soil amendments strategies to improve water-use efficiency and productivity of maize under different irrigation conditions. Agric. Water Manag. 210, 88–95.
Blum, A., 2009. Effective use of water (EUW) and not water-use efficiency (WUE) is the target of crop yield improvement under drought stress. Field Crops Res. 112, 119–123.
Bouwman, A.F., Beusen, A.H.W., Billen, G., 2009. Human alteration of the global nitrogen and phosphorus soil balances for the period 1970-2050. Global Biogeochem. Cycles 23 GB0A04.
Bouwman, L., Goldewijk, K.K., Van Der Hoek, K.W., Beusen, A.H.W., Van Vuuren, D.P., Willems, J., Rufino, M.C., Stehfest, E., 2013. Exploring global changes in nitrogen and phosphorus cycles in agriculture induced by livestock production over the 1900-2050 period. Proc. Natl. Acad. Sci. U.S.A. 110, 20882–20887.
Chadwick, D., Jia, W., Tong, Y., Yu, G., Shen, Q., Chen, Q., 2015. Improving manure nutrient management towards sustainable agricultural intensification in China. Agric. Ecosyst. Environ. 209, 34–46.
Chen, X., Cui, Z., Fan, M., Vitousek, P., Zhao, M., Ma, W., Wang, Z., Zhang, W., Yan, X., Yang, J., Deng, X., Gao, Q., Zhang, Q., Guo, S., Ren, J., Li, S., Ye, Y., Wang, Z., Huang, J., Tang, Q., Sun, Y., Peng, X., Zhang, J., He, M., Zhu, Y., Xue, J., Wang, G., Wu, L., An, N., Wu, L., Ma, L., Zhang, W., Zhang, F., 2014a. Producing more grain with lower environmental costs. Nature 514, 486–489.
Chen, Z., Ding, W., Luo, Y., Yu, H., Xu, Y., Müller, C., Xu, X., Zhu, T., 2014b. Nitrous oxide emissions from cultivated black soil: a case study in Northeast China and global estimates using empirical model. Global Biogeochem. Cycles 28, 1311–1326.
De Neve, S., Hofman, G., 2002. Quantifying soil water effects on nitrogen mineralization from soil organic matter and from fresh crop residues. Biol. Fertil. Soils 35, 379–386.
Deng, W., Wang, Y., Liu, Z., Cheng, H., Xue, Y., 2014. HemI: a toolkit for illustrating heatmaps. PLoS One 9, e111988.
Edmeades, D.C., 2003. The long-term effects of manures and fertilisers on soil productivity and quality: a review. Nutr. Cycl. Agroecosystems 66, 165–180.
Ercoli, L., Lulli, L., Mariotti, M., Masoni, A., Arduini, I., 2008. Post-anthesis dry matter and nitrogen dynamics in durum wheat as affected by nitrogen supply and soil water availability. Eur. J. Agron. 28, 138–147.
Fang, Q., Yu, Q., Wang, E., Chen, Y., Zhang, G., Wang, J., Li, L., 2006. Soil nitrate accumulation, leaching and crop nitrogen use as influenced by fertilization and irrigation in an intensive wheat–maize double cropping system in the North China Plain. Plant Soil 284, 335–350.
Ferrante, A., Savin, R., Slafer, G.A., 2015. Relationship between fruiting efficiency and grain weight in durum wheat. Field Crops Res. 177, 109–116.
Fischer, R.A., 2011. Wheat physiology: a review of recent developments. Crop Pasture Sci. 62, 95–114.
Foulkes, M.J., Slafer, G.A., Davies, W.J., Berry, P.M., Sylvester-Bradley, R., Martre, P., Calderini, D.F., Griffiths, S., Reynolds, M.P., 2011. Raising yield potential of wheat. III. Optimizing partitioning to grain while maintaining lodging resistance. J. Exp. Bot. 62, 469–486.
Gaju, O., Reynolds, M.P., Sparkes, D.L., Foulkes, M.J., 2009. Relationships between large-spike phenotype, grain number, and yield potential in spring wheat. Crop Sci. 49, 961.
Gaju, O., Reynolds, M.P., Sparkes, D.L., Mayes, S., Ribas-Vargas, G., Crossa, J., Foulkes, M.J., 2014. Relationships between physiological traits, grain number and yield potential in a wheat DH population of large spike phenotype. Field Crops Res. 164, 126–135.
Galloway, J., Dentener, F., Burke, M., Dumont, E., Bouwman, A.F., Kohn, R.A., Mooney, H.A., Seitzinger, S., Kroeze, C., 2010. The impact of animal production systems on the nitrogen cycle. In: In: Steinfeld, H., Mooney, H., Schneider, F., Neville, L. (Eds.), Livestock in a Changing Landscape 1. Drivers, consequences and responses. Island Press, Washington, USA, pp. 83–95.
Godfray, H.C.J., Beddington, J.R., Crute, I.R., Haddad, L., Lawrence, D., Muir, J.F., Pretty, J., Robinson, S., Thomas, S.M., Toulmin, C., 2010. Food Security: the challenge of feeding 9 billion people. Science 327, 812–818.
Guntiñas, M.E., Leirós, M.C., Trasar-Cepeda, C., Gil-Sotres, F., 2012. Effects of moisture and temperature on net soil nitrogen mineralization: a laboratory study. Eur. J. Soil Biol. 48, 73–80.
Guo, J., Liu, X., Zhang, Y., Shen, J., Han, W., Zhang, W., Christie, P., Goulding, K.W.T., Vitousek, P.M., Zhang, F., 2010. Significant acidification in major Chinese croplands. Science 327, 1008–1010.
Hedges, L.V., Gurevitch, J., Curtis, P.S., 1999. The meta-analysis of response ratios in experimental ecology. Ecology 80, 1150–1156.
Heggenstaller, A.H., Anex, R.P., Liebman, M., Sundberg, D.N., Gibson, L.R., 2008. Productivity and nutrient dynamics in bioenergy double-cropping systems. Agron. J. 100, 1740–1748.
Howard, A.E., 2006. Agronomic thresholds for soil phosphorus in Alberta: a review. In: Alberta Soil Phosphorus Limits Project. Volume 5: Background Information and Reviews. Alberta Agriculture. Food and Rural Development, Lethbridge, AB, pp. 42.
Li, Q., Dong, B., Qiao, Y., Liu, M., Zhang, J., 2010. Root growth, available soil water, and water-use efficiency of winter wheat under different irrigation regimes applied at different growth stages in North China. Agric. Water Manag. 97, 1676–1682.
Li, Y., Cui, Z., Ni, Y., Zheng, M., Yang, D., Jin, M., Chen, J., Wang, Z., Yin, Y., 2016. Plant density effect on grain number and weight of two winter wheat cultivars at different spikelet and grain positions. PLoS One 11, e0155351.
Li, J., Xu, X., Lin, G., Wang, Y., Liu, Y., Zhang, M., Zhou, J., Wang, Z., Zhang, Y., 2018. Micro-irrigation improves grain yield and resource use efficiency by co-locating the roots and N-fertilizer distribution of winter wheat in the North China Plain. Sci. Total Environ. 643, 367–377.
Liu, X., Zhang, Y., Han, W., Tang, A., Shen, J., Cui, Z., Vitousek, P., Erisman, J.W., Goulding, K., Christie, P., Fangmeier, A., Zhang, F., 2013. Enhanced nitrogen deposition over China. Nature 494, 459–462.
Liu, Z., Gao, J., Gao, F., Dong, S., Liu, P., Zhao, B., Zhang, J., 2018. Integrated agronomic practices management improve yield and nitrogen balance in double cropping of winter wheat-summer maize. Field Crops Res. 221, 196–206.
Lu, C., Fan, L., 2013. Winter wheat yield potentials and yield gaps in the North China Plain. Field Crops Res. 143, 98–105.
Ma, L., Ma, W., Velthof, G.L., Wang, F., Qin, W., Zhang, F., Oenema, O., 2010. Modeling nutrient flows in the food chain of China. J. Environ. Qual. 39, 1279–1289.
Meena, R.P., Karnam, V., Tripathi, S.C., Jha, A., Sharma, R.K., Singh, G.P., 2019. Irrigation management strategies in wheat for efficient water use in the regions of depleting water resources. Agric. Water Manag. 214, 38–46.
Miller, J., Beasley, B., Drury, C., Larney, F., Hao, X., 2016. Surface soil salinity and soluble salts after 15 applications of composted or stockpiled manure with straw or woodchips. Compost Sci. Util. 25, 36–47.

Mortada, S., Abou Najm, M., Yassine, A., El Fadel, M., Alamiddine, I., 2018. Towards sustainable water-food nexus: an optimization approach. J. Clean. Prod. 178, 408–418.

Olesen, J.E., Mortensen, J.V., Jørgensen, L.N., Andersen, M.N., 2000. Irrigation strategy, nitrogen application and fungicide control in winter wheat on a sandy soil. I. Yield, yield components and nitrogen uptake. J. Agric. Sci. 134, 1–11.

Osenberg, C.W., Sarnelle, O., Cooper, S.D., 1997. Effect size in ecological experiments: the application of biological models in meta-analysis. Am. Nat. 150, 798–812.

Pedersen, I.F., Rubæk, G.H., Nyord, T., Sørensen, P., 2020. Row-injected cattle slurry can replace mineral P starter fertiliser and reduce P surpluses without compromising final yields of silage maize. Eur. J. Agron. 116, 126057.

Rosas, F., Babcock, B.A., Hayes, D.J., 2015. Nitrous oxide emission reductions from cutting excessive nitrogen fertilizer applications. Clim. Change 132, 353–367.

Shi, Y., Yu, Z., Man, J., Ma, S., Gao, Z., Zhang, Y., 2016. Tillage practices affect dry matter accumulation and grain yield in winter wheat in the North China Plain. Soil Tillage Res. 160, 73–81.

Slafer, G.A., Savin, R., Sadras, V.O., 2014. Coarse and fine regulation of wheat yield components in response to genotype and environment. Field Crops Res. 157, 71–83.

Slafer, G.A., Elia, M., Savin, R., García, G.A., Terrile, I.I., Ferrante, A., Miralles, D.J., González, F.G., 2015. Fruiting efficiency: an alternative trait to further rise wheat yield. Food Energy Secur. 4, 92–109.

Tang, Q., Zhang, C., 2013. Data Processing System (DPS) software with experimental design, statistical analysis and data mining developed for use in entomological research. Insect Sci. 20, 254–260.

Thapa, S., Xue, Q., Jessup, K.E., Rudd, J.C., Liu, S., Pradhan, G.P., Devkota, R.N., Baker, J., 2017. More recent wheat cultivars extract more water from greater soil profile depths to increase yield in the Texas High Plains. Agron. J. 109, 2771–2780.

Thapa, S., Xue, Q., Jessup, K.E., Rudd, J.C., Liu, S., Marek, T.H., Devkota, R.N., Baker, J.A., Baker, S., 2019. Yield determination in winter wheat under different water regimes. Field Crops Res. 233, 80–87.

Wang, F., Dou, Z., Ma, L., Ma, W., Sims, J.T., Zhang, F., 2010. Nitrogen mass flow in China's animal production system and environmental implications. J. Environ. Qual. 39, 1537–1544.

Wang, C., Li, X., Gong, T., Zhang, H., 2014. Life cycle assessment of wheat-maize rotation system emphasizing high crop yield and high resource use efficiency in Quzhou County. J. Clean. Prod. 68, 56–63.

Wang, B., Zhang, Y., Hao, B., Xu, X., Zhao, Z., Wang, Z., Xue, Q., 2016. Grain yield and water use efficiency in extremely-late sown winter wheat cultivars under two irrigation regimes in the North China Plain. PLoS One 11, e0153695.

Wang, X., Ren, Y., Zhang, S., Chen, Y., Wang, N., 2017. Applications of organic manure increased maize (*Zea mays* L.) yield and water productivity in a semi-arid region. Agric. Water Manag. 187, 88–98.

Wang, Y., Zhang, Y., Zhang, R., Li, J., Zhang, M., Zhou, S., Wang, Z., 2018. Reduced irrigation increases the water use efficiency and productivity of winter wheat-summer maize rotation on the North China Plain. Sci. Total Environ. 618, 112–120.

Xia, L., Lam, S.K., Yan, X., Chen, D., 2017. How does recycling of livestock manure in agroecosystems affect crop productivity, reactive nitrogen losses, and soil carbon balance? Environ. Sci. Technol. 51, 7450–7457.

Xiao, G., Zhao, Z., Liang, L., Meng, F., Wu, W., Guo, Y., 2019. Improving nitrogen and water use efficiency in a wheat-maize rotation system in the North China Plain using optimized farming practices. Agric. Water Manag. 212, 172–180.

Xu, X., Zhang, M., Li, J., Liu, Z., Zhao, Z., Zhang, Y., Zhou, S., Wang, Z., 2018. Improving water use efficiency and grain yield of winter wheat by optimizing irrigations in the North China Plain. Field Crops Res. 221, 219–227.

Xue, Q., Zhu, Z., Musick, J.T., Stewart, B.A., Dusek, D.A., 2006. Physiological mechanisms contributing to the increased water-use efficiency in winter wheat under deficit irrigation. J. Plant Physiol. 163, 154–164.

Xue, Q., Rudd, J.C., Liu, S., Jessup, K.E., Devkota, R.N., Mahan, J.R., 2014. Yield determination and water-use efficiency of wheat under water-limited conditions in the U.S. Southern High Plains. Crop Sci. 54, 34–47.

Ying, H., Ye, Y., Cui, Z., Chen, X., 2017. Managing nitrogen for sustainable wheat production. J. Clean. Prod. 162, 1308–1316.

Zhang, X., Davidson, E.A., Mauzerall, D.L., Searchinger, T.D., Dumas, P., Shen, Y., 2015. Managing nitrogen for sustainable development. Nature 528, 51–59.

Zhang, K., Zhao, J., Wang, X., Xu, H., Zang, H., Liu, J., Hu, Y., Zeng, Z., 2019. Estimates on nitrogen uptake in the subsequent wheat by above-ground and root residue and rhizodeposition of using peanut labeled with ^{15}N isotope on the North China Plain. J. Integr. Agric. 18, 571–579.

Zhao, D., Shen, J., Lang, K., Liu, Q., Li, Q., 2013. Effects of irrigation and wide-precision planting on water use, radiation interception, and grain yield of winter wheat in the North China Plain. Agric. Water Manag. 118, 87–92.

Zhao, Z., Qin, X., Wang, Z., Wang, E., 2018. Performance of different cropping systems across precipitation gradient in North China Plain. Agric. For. Meteorol. 259, 162–172.

Zhao, J., Chu, Q., Shang, M., Meki, M.N., Norelli, N., Jiang, Y., Yang, Y., Zang, H., Zeng, Z., Jeong, J., 2019a. Agricultural Policy Environmental eXtender (APEX) simulation of spring peanut management in the North China Plain. Agronomy 9, 443.

Zhao, J., Yang, Y., Zhang, K., Jeong, J., Zeng, Z., Zang, H., 2019b. Does crop rotation yield more in China? A meta-analysis. Field Crops Res. 245, 107659.

Zheng, C., Liu, J., Cao, G., Kendy, E., Wang, H., Jia, Y., 2010. Can China cope with its water crisis? -perspectives from the North China Plain. Ground Water 48, 350–354.

Zhou, M., Zhu, B., Brüggemann, N., Dannenmann, M., Wang, Y., Butterbach-Bahl, K., 2016. Sustaining crop productivity while reducing environmental nitrogen losses in the subtropical wheat-maize cropping systems: a comprehensive case study of nitrogen cycling and balance. Agric. Ecosyst. Environ. 231, 1–14.