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An alternative water-fertilizer-saving management practice for wheat-maize cropping system in the North China Plain: Based on a 4-year field study

Haoru Li [a,b], Xiaoli Li [a,b], Xurong Mei [a,b], Vinay Nangia [c], Rui Guo [a,b], Weiping Hao [a,b,*], Jiandong Wang [a,b,*]

[a] Institute of Environment and Sustainable Development in Agriculture, Chinese Academy of Agricultural Sciences, Beijing 100081, China
[b] Key Laboratory of Dryland Agriculture, Ministry of Agriculture and Rural Affairs of the People's Republic of China, Beijing 100081, China
[c] International Center for Agricultural Research in Dry Areas, Rabat 6299, Morocco

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ABSTRACT

Developing an alternative water-fertilizer-saving management practice for winter wheat-summer maize double cropping system in the North China Plain (NCP) is urgent to address severe water scarcity and adverse environmental impacts. A four-year field experiment in split plot design was conducted to evaluate the effects of supplemental drip irrigation on grain yield, water use efficiency (WUE), nitrogen use efficiency (NUE), nitrogen (N) loss and economic benefits, keeping three supplemental drip irrigation times (DI_0, no irrigation after emergence; DI_3, irrigation once at wheat jointing, once at maize seedling and once at maize jointing; DI_5, irrigation once at wheat jointing, once at wheat anthesis, once at maize seedling, once at maize jointing and once at maize tasseling) in the main plots and three N fertilizer rates (N_0, no N fertilizer; $N_{60\%}$, 60% of the local recommended N fertilizer rate, 272 kg N ha^{-1} yr^{-1}; $N_{100\%}$, 100% of the local recommended N fertilizer rate, 453 kg N ha^{-1} yr^{-1}) in the sub plots. The traditional surface irrigation regime was also conducted as control (CK) under local recommended N fertilizer at 453 kg N ha^{-1} yr^{-1}. The results showed that $DI_5N_{60\%}$ achieved the highest WUE in wheat (1.93 kg m^{-3}) and maize (3.00 kg m^{-3}) on average, which was 3.0% and 25.3% higher compared to CK, respectively. The highest partial factor productivity from applied N (PEP_N) in wheat and maize were also observed in $DI_5N_{60\%}$ (56.8 kg kg^{-1} and 56.3 kg kg^{-1}, respectively) on average, which was 54.0% and 74.0% higher compared to CK, respectively. For winter wheat-summer maize double cropping system, $DI_5N_{60\%}$ can generally achieve similar crop yield and net income but reduce irrigation and N fertilizer use and N loss compared to CK. Therefore, $DI_5N_{60\%}$ was considered as an alternative water-fertilizer-saving management practice for winter wheat-summer maize double cropping system in the NCP. Moreover, the optimized combination of irrigation amount and N fertilizer rate corresponding simultaneously to higher crop yield, WUE and net income were determined by using the response surface methodology based on binary quadratic regression analysis, and the optimal irrigation amount were 165 mm and 90 mm, optimal N rates were 186 kg N ha^{-1} and 185 kg N ha^{-1} for winter wheat and summer maize, respectively.

1. Introduction

The North China Plain (NCP), which produces 60% and 31% of nation's wheat and maize, respectively (NBSC, 2021), is one of the most important grain production regions in China and winter wheat-summer maize double cropping system is the main cropping system in this region. Winter wheat production relies mainly on supplemental irrigation by exploiting groundwater in the NCP, because only 20%–30% of the annual rainfall concentrates in the winter wheat growing season, which is far from meeting the growth needs of winter wheat (Zhang et al., 2003; Fang et al., 2010; Jha et al., 2019). Although summer maize is grown in the rainy season with high temperatures, unevenly distributed rainfall caused short-term droughts often occur in summer maize, so supplemental irrigation is also required during the critical growth stages

* Corresponding authors at: Institute of Environment and Sustainable Development in Agriculture, Chinese Academy of Agricultural Sciences, Beijing 100081, China.

E-mail addresses: haoweiping@caas.cn (W. Hao), wangjiandong@caas.cn (J. Wang).

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of summer maize (Yan et al., 2017). To achieve high crop yields, excessive irrigation (up to 667 mm yr^{-1}, Shi et al., 2013) and over nitrogen (N) fertilization (550–600 kg N ha^{-1} yr^{-1}, Ju et al., 2009; Tan et al., 2017) have been adopted as the crucial farming practices since the 1980s. However, long-term overexploitation of groundwater has led to the groundwater table declining by about 1 m annually over the last 20 years (IGSNRR, 2016), which negatively affects the sustainable agricultural development in the NCP (Niu et al., 2019). In addition, the traditional N fertilizer rate is substantially higher than the crop requirement (Liu et al., 2003), which inevitably leads to large N losses, such as greenhouse gas emissions, ammonia volatilization and other forms of N pollution (Tan et al., 2017). To address these challenges, it is vitally important to develop an alternative water-fertilizer-saving management practice for sustainable production in the NCP.

Applying water and fertilizer at critical growth stages of the crop could improve photosynthesis and biomass production, and ultimately increase yield, water use efficiency (WUE) and N use efficiency (NUE). Many previous studies demonstrated that jointing and anthesis are the critical stages of wheat for grain yield. For example, Xu et al. (2018) recommended two irrigations at jointing and anthesis of wheat with 150 mm irrigation amount. Lv et al. (2011) proposed a single application of 60–70 mm at jointing, whereas Zhang et al. (2012) recommended one irrigation application during recovery to the jointing stage with 70–90 mm. Previous studies also examined the effects of supplemental irrigation at tasseling on WUE and maize yield (Igbadun et al., 2007; Li and Sun, 2016). However, all the above recommendations were based on the traditional surface irrigation method. To gain further benefit, supplemental irrigation with effective water-saving technology consideration of precipitation, soil water storage and crop evapotranspiration needs to be developed urgently (Man et al., 2014).

Drip fertigation can provide appropriate irrigation amount and N rate in crop root zone by more precise and timely manner than traditional surface irrigation, which has been confirmed to be an efficient irrigation and fertilization technology (Abalos et al., 2014; Farneselli et al., 2015; Yan et al., 2020). We hypothesized that under supplemental drip fertigation with optimal N rate at the critical growth stage of crop, WUE, NUE and economic benefit could be further improved, and N loss could be reduced. We conducted a field experiment to study the effects of different supplemental drip irrigation times with different N fertilizer rates on crop yield, WUE, NUE, N loss and economic benefit. The aims of this study were (1) to study crop yield, crop evapotranspiration, WUE, NUE and N loss responses to different irrigation and fertilization management; (2) to analyze the economic benefits of winter wheat-summer maize double cropping system under different irrigation and fertilization management; (3) to optimize the combination of irrigation amount and N rate to reach optimal yield, WUE and net income values simultaneously.

2. Materials and methods

2.1. Experimental site

A field experiment on winter wheat (*Triticum aestivum* L.)-summer maize (*Zea mays* L.) double cropping system was conducted during four consecutive years (2015–2019) at the Dry-land Farming Research Institute of Hebei Academy of Agricultural and Forestry Sciences (37°53′ N, 115°42′ E, 31 m above sea level) locating at Hengshui City, Hebei Province in the NCP. This site has a warm temperate, sub-humid continental monsoon climate. The 30-year mean annual temperature and precipitation were 14.4 °C and 582 mm, respectively, and 70%–80% of precipitation occurs in the summer maize growing season (from June to September). The daily mean temperature and precipitation at the experimental site during 2015–2019 are shown in Fig. 1. The soil in this site is a sandy loam fluvo-aquic soil (Calcaric Cambisols, FAO). The basic physical and chemical properties of the soil (0–160 cm layer) is shown in Table 1.

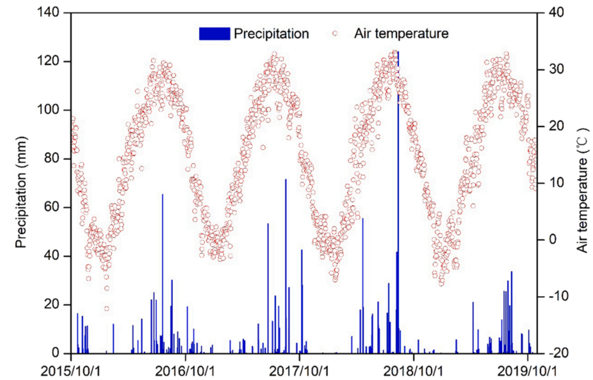

Fig. 1. Daily mean air temperature and precipitation during the four growing seasons of 2015–2019 at the experimental site.

2.2. Experimental design and arrangement

The experiment was used a split-plot design with three replicates. The three main-plot treatments were different supplemental drip irrigation times {0 times (no irrigation after emergence), 3 times (irrigation once at wheat jointing, once at maize seedling and once at maize jointing) and 5 times (irrigation once at wheat jointing, once at wheat anthesis, once at maize seedling, once at maize jointing and once at maize tasseling), referred as DI_0, DI_3 and DI_5, respectively}, the three sub-plot treatments were different N fertilizer rate (0, 60% of local recommended N rate, 100% of local recommended N rate, referred as N_0, $N_{60\%}$ and $N_{100\%}$, respectively). In 2015–2016, 140% of local recommended N rate (referred as $N_{140\%}$) was conducted to evaluate the effects of over fertilization on the crop yields, WUE and partial factor productivity from applied N (PEP_N), which showed that the crop yields and WUE in $N_{140\%}$ was no significant difference but PEP_N in $N_{140\%}$ was significantly lower compared to $N_{60\%}$ and $N_{100\%}$ irrespective of supplemental drip irrigation times (see supplementary for more information). Traditional surface method through plastic pipe was also conducted as control (CK) under local recommended N fertilizer rate at 228 kg N ha^{-1} and 225 kg N ha^{-1} for wheat and maize, respectively. Each sub-plot size was 60 m^2 (6 m × 10 m), and with a 2 m wide isolation area preventing water penetration between contiguous plots. The winter wheat cultivar 'Jimai 22' was planted on 17 October 2015, 20 October 2016, 22 October 2017 and 8 October 2018 at a seeding rate of 262.5 kg ha^{-1} with 15 cm row spacing. After harvesting the winter wheat, the summer maize cultivar 'Zhengdan 958' was planted at a density 5.6 seedings m^{-2} with 60 cm row on 19 June 2016, 16 June 2017, 21 June 2018 and 19 June 2019. The crop varieties and planting densities were chose depending on the local agricultural practices. Pesticides and herbicides were used according to actual situation.

2.3. Irrigation and fertilization management

The drip fertigation system was composed of mainlines, submain lines, laterals, drippers, a sand filter, a screen filter, a gate valve, a flow meter and a liquamatic piston fertilizer pump (MixRite 2504 H, Tefen, Israel) to control the irrigation and N application. The laterals with in-line drippers of 1.9 L h^{-1} flow rate at 0.3 m apart, were laid parallel to the crop rows, and each lateral supplied two rows of wheat or one row of maize. The source of irrigation was groundwater (well depth > 90 m). Irrigation amount was based on soil moisture, which was determined gravimetrically at jointing and anthesis of wheat, seedling, jointing and tasseling of maize, calculating as follows (Zhang et al., 2018):

$$I = 0.1 \times r \times z \times p \times (\theta_{max} - \theta_{min})/\eta \quad (1)$$

where I (mm) was the irrigation amount; r (g cm^{-3}) was the bulk density; z (m) was the designed wetting depth, which was considered as

Table 1
The basic physical and chemical properties of the soil (0–160 cm layer) before the establishment of the experiment.

Soil layer (cm)	Clay (%)	Bulk density (g cm^{-3})	pH	Field capacity (cm^3 cm^{-3})	Saturated water content (cm^3 cm^{-3})	Wilting point (cm^3 cm^{-3})	Organic matter (g kg^{-1})	Alkali-hydrolyzable N (mg kg^{-1})	Extractable Olsen P (mg kg^{-1})	Exchangeable K (mg kg^{-1})
0–20	28.1	1.37	8.1	0.314	0.471	0.141	16.9	74.2	8.7	102.0
20–40	29.7	1.46	8.1	0.324	0.513	0.187	12.3	44.6	1.3	116.6
40–60	35.9	1.31	8.0	0.374	0.522	0.206	12.2	26.8	1.9	137.2
60–80	42.9	1.35	8.0	0.400	0.527	0.240	11.9	30.8	7.2	149.8
80–100	33.8	1.43	7.9	0.353	0.484	0.182	9.9	21.8	6.0	128.7
100–120	45.0	1.52	7.9	0.357	0.453	0.167	10.0	27.9	6.8	144.0
120–140	33.7	1.39	7.9	0.396	0.469	0.172	10.5	28.6	8.0	167.7
140–160	38.0	1.36	7.9	0.429	0.498	0.206	10.8	17.9	5.5	160.6

60 cm due to the root of the wheat and maize mainly distributing in the 0–60 m soil depth; p was the percentage of wetted area (80%); Θ_{max} (%) was the upper threshold soil moisture, which was considered as 90% field water holding capacity; Θ_{min} (%) was lower threshold soil moisture, which was the average soil gravimetric water content in the effective rooting depth at the time of irrigation; and η was the application efficiency (0.95). Before winter wheat was sowed, 120 mm water was applied for all the treatments to guarantee uniform germination using the surface irrigation method through plastic pipe and no irrigation water was applied in 2017–2018 due to the rainfall pre-sowing.

Starter N (40% of the total N) was surface broadcasted by hand at pre-sowing and incorporated into the topsoil (10–15 cm depth) by rotary tillage for all the treatments. Topdressing N (the other 60% of the total N) for CK was surface broadcasted by hand at jointing, while which for drip fertigated treatments was applied by dissolving urea in the irrigation water. P and K were applied as basal dressing at typical local rates (112 kg P_2O_5 ha^{-1} and 112 kg K_2O ha^{-1} for winter wheat and 90 kg P_2O_5 ha^{-1} and 90 kg K_2O ha^{-1} for summer maize, respectively) to all the treatments as single superphosphate and potassium sulfate prior to planting in each growing season. The specific irrigation amount and N fertilizer rate applied to each treatment during the four growing seasons are shown in Table 2.

2.4. Sampling and measurements

2.4.1. Yields and yield components

For wheat, grain yield was determined according to three separate sampling areas of 1 m^2 in the center of each plot at maturity. The grains were oven-dried and weighed after threshing by hand. The spike number was counted from two adjoining 1 m long rows at two randomly selected spots within each plot, and the kernel number per spike was also recorded based on these samples. For maize, grain yield was determined by harvesting all plants within a sampling area 5 m long and 1.8 m wide in the middle of each plot at maturity. Twenty plants in each subplot were selected for the determination of 1000-kernel weight, ear number and kernel number per ear.

2.4.2. Plant N concentration

For wheat, three rows of plants with 0.2 m long were randomly chosen from each plot and separated into culms, leaves and grain at maturity. For maize, five plants from each plot were selected and separated into culms, leaves, cobs, subtending leaves and grain at harvest. These samples were oven-heated at 105 °C for 0.5 h, dried at 75 °C for 48 h to a constant weight, and then weighed and grinded through a 0.25 mm sieve to measure the N concentrations using the micro-Kjeldahl method.

2.4.3. Soil water and nitrate N content

The volumetric soil water content was measured in each plot (20 cm increments from 0 to 160 cm) before sowing and after harvesting with a time-domain reflectometer (TRIME-IT, Germany). Extra measurements were needed to take before and after irrigation or precipitation. The tubes were installed to the 160 cm soil in the middle of each experimental plot. The gravimetric method was used to test and calibrate the measurements of the time-domain reflectometer. The soil nitrate N content was extracted from 10 g subsamples grinded through a 2 mm sieve using 50 mL of 2 mol L^{-1} KCl solution and shaking for 1 h. After filtration, the extracts were measured immediately the NO_3^--N and NH_4^+-N concentrations with a continuous flow analyzer (AA3, Bran Luebbe, Germany).

2.4.4. Evapotranspiration and water use efficiency

The evapotranspiration (ET_a, mm) was calculated according to the water balance formula (Huang et al., 2005):

$$ET_a = P + I + C - \Delta S - R - D \quad (2)$$

where P (mm) was the precipitation during the growing season; I (mm) was the irrigation amount; C (mm) was the upward flow into root zone, which was considered as zero because there was no high groundwater problem in the area; ΔS (mm) was the soil water storage in the soil profile (0–160 cm in depth) from sowing to harvesting; R (mm) was the surface runoff, which was zero in the experiment because the field was flat; D (mm) was the drainage below the measured root zone and was estimated as followings (Gong and Li, 1995):

$$D = \sum_{i=1}^{n}(S_{ib} + I_i - F) + \sum_{j=1}^{n}(S_{jb} + P_j - F) \quad (3)$$

where S_{ib} (mm) and S_{jb} (mm) was the soil water storage change in the 0–160 cm soil profile before the i irrigation and the j precipitation, respectively; I_i (mm) was the i irrigation amount; P_j (mm) was the j precipitation; F (mm) was the biggest soil water storage in 0–160 cm soil profile. While if $S_{ib} + I_i$ or $S_{jb} + P_j \le F$, the drainage was assumed to be zero.

Water use efficiency (WUE, kg m^{-3}) was calculated as followings (Huang et al., 2005):

$$WUE = 0.1 \times \frac{Y}{ET_a} \quad (4)$$

where Y (kg ha^{-1}) was the grain yield and ET_a (mm) was the evapotranspiration during the entire growth period.

2.4.5. Nitrogen loss and nitrogen use efficiency

The crop N uptake (kg N ha^{-1}) was calculated as followings (Dai et al., 2016):

$$N_{uptake} = \frac{\sum N_c \times DW}{1000} \quad (5)$$

where N_{uptake} (kg N ha^{-1}) was the aboveground N uptake; N_c (g kg^{-1}) was the N concentration in different organs; DW (kg ha^{-1}) the corresponding dry weight of different organs; and 1000 is the conversion factor.

The mineral N accumulation (kg ha^{-1}) was calculated as followings:

Table 2
Irrigation amount and nitrogen (N) fertilizer rate at different growing stages for all the treatments during the four growing seasons of 2015–2019.

Treatment	Winter wheat: Irrigation times	Irrigation stage	Irrigation amount (mm) 2015–2016	2016–2017	2017–2018	2018–2019	N fertilizer rate (kg N ha^{-1})	Summer maize: Irrigation times	Irrigation stage	Irrigation amount (mm) 2016	2017	2018	2019	N fertilizer rate (kg N ha^{-1})
DI_0N_0	0	——	——	0	0	0	0	0	——	——	0	0	0	0
$DI_0N_{60\%}$	0	——	0	0	0	0	137	0	——	0	0	0	0	135
$DI_0N_{100\%}$	0	——	0	0	0	0	228	0	——	0	0	0	0	225
$DI_0N_{140\%}$	0	——	0	——	——	——	319	0	——	0	——	——	——	315
DI_3N_0	1	——	——	50	40	55	0	2	——	——	100	100	70	0
$DI_3N_{60\%}$	1	Jointing	40	50	40	55	137	2	Seedling, jointing	100	100	100	70	135
$DI_3N_{100\%}$	1	Jointing	40	50	40	55	228	2	Seedling, jointing	100	100	100	70	225
$DI_3N_{140\%}$	1	Jointing	40	——	——	——	319	2	Seedling, jointing	100	——	——	——	315
DI_5N_0	2	——	——	110	100	120	0	3	——	——	110	115	75	0
$DI_5N_{60\%}$	2	Jointing, anthesis	100	110	100	120	137	3	Seedling, jointing, tasseling	120	110	115	75	135
$DI_5N_{100\%}$	2	Jointing, anthesis	100	110	100	120	228	3	Seedling, jointing, tasseling	120	110	115	75	225
$DI_5N_{140\%}$	2	Jointing, anthesis	100	——	——	——	319	3	Seedling, jointing, tasseling	120	——	——	——	315
CK	2	Jointing, anthesis	240	240	240	240	228	1	Pre-sowing	120	120	120	120	225

Note: Before winter wheat was sowed, 120 mm water was applied for all the treatments to guarantee uniform germination using the surface irrigation through plastic pipe and no irrigation water was applied in 2017–2018 due to the rainfall pre-sowing. "——" means no data. DI_0 indicates no irrigation after emergence; DI_3 indicates irrigation once at wheat jointing, once at maize seedling and once at maize jointing; DI_5 indicates irrigation once at wheat jointing, once at wheat anthesis, once at maize seedling, once at maize jointing and once at maize tasseling; N_0, $N_{60\%}$, $N_{100\%}$ and $N_{140\%}$ represent 0, 60%, 100% and 140% of local recommended N fertilizer rate, respectively. CK represents traditional surface irrigation method under 100% of local recommended N fertilizer rate at 453 kg N ha^{-1} yr^{-1}. In 2015–2016, different N fertilizer rate treatments includes $N_{60\%}$, $N_{100\%}$ and $N_{140\%}$. In 2016–2019, different N fertilizer rate treatments includes N_0, $N_{60\%}$ and $N_{100\%}$.

$$\text{Mineral N } accumulation = \frac{\text{T} \times \text{BD} \times \text{Mineral N } content}{10} \quad (6)$$

where T (cm) was the soil thickness; BD (g cm^{-3}) was the soil bulk density; Mineral N content (mg kg^{-1}) was the sum of the NO_3^--N and NH_4^+-N; and 0.1 was the conversion coefficient.

The N fertilizer loss to the environment was calculated as followings (Chen et al., 2021):

$$N_{loss} = N_{initial} + N_{fertilizer} - N_{uptake} - N_{residual} \quad (7)$$

where $N_{initial}$ (kg N ha^{-1}) was initial mineral N content in the 0–160 cm soil profile before planting; $N_{fertilizer}$ (kg N ha^{-1}) was the N fertilizer rate; N_{uptake} (kg N ha^{-1}) was the crop N uptake; and $N_{residual}$ (kg N ha^{-1}) was the residual mineral N accumulation in the 0–160 cm soil profile at harvest.

The nitrogen use efficiency, such as recovery efficiency (RE_N), agronomic efficiency (AE_N) and partial factor productivity from applied N (PFP_N), were calculated as followings (Ladha et al., 2005):

$$RE_N = \frac{N_{uptake}^{T} - N_{uptake}^{CK}}{N_{fertilizer}} \quad (8)$$

where N_{uptake}^{T} (kg N ha^{-1}) and N_{uptake}^{CK} (kg N ha^{-1}) were the aboveground N uptake of the fertilized and no-fertilized treatments at harvest, respectively; and $N_{fertilizer}$ (kg N ha^{-1}) was the N fertilizer rate.

$$AE_N = \frac{Y_T - Y_{CK}}{N_{fertilizer}} \quad (9)$$

where Y_T (kg ha^{-1}) and Y_{CK} (kg ha^{-1}) were the crop yields of the fertilized and no-fertilized treatments at harvest, respectively; and $N_{fertilizer}$ (kg N ha^{-1}) was the N fertilizer rate.

$$PEP_N = \frac{Y_T}{N_{fertilizer}} \quad (10)$$

where Y_T (kg ha^{-1}) was the crop yield of the fertilized treatment; and $N_{fertilizer}$ (kg N ha^{-1}) was the N fertilizer rate.

2.4.6. Economic benefit

The net income of agricultural production (Chinese Yuan per ha, CNY ha^{-1}) was calculated (Uygan et al., 2021) as followings:

$$\text{Net income} = P_g - T_c \quad (11)$$

where P_g was the gross profit (CNY ha^{-1}), which equals the crop yield (kg ha^{-1}) multiple sales price of grains (CNY kg^{-1}); and T_c (CNY ha^{-1}) was the total cost, including the cost of irrigation material, machinery, power, labor, seed, herbicides, pesticides, water and fertilizer.

2.5. Statistical analysis

Analysis of variance (ANOVA) was performed using SAS 9.2 (SAS Institute Inc., Cary, NC, USA), and the difference between the treatment was evaluated using Least-Significant Difference (LSD) multiple comparison tests at the P = 0.05 level. The response surface methodology was used to determine the optimal irrigation amount and N fertilizer rate, which allowed the graphical visualization of responses of grain yield, WUE, PEP_N and net income to irrigation amount and N rate (Thompson et al., 2000; Liyana-Pathirana and Shahidi, 2005; Wang et al., 2018). Origin 2021b (OriginLab Corp., Northampton, MA, USA) was used to construct the graphs.

3. Results

3.1. Grain yield and yield components

For wheat, the grain yield increased significantly ($P < 0.05$) by

20.9% and 21.7% under DI_3 and DI_5 compared to the DI_0 (5753.7 kg ha^{-1}), respectively (Table 3). The similar trends were found in spike number and kernels per spike (Table 3). DI_5 significantly increased 1000-grain weight by 4.2% and 4.4% as compared to DI_0 and DI_3, respectively. The wheat grain yield increased significantly by 18.4% and 24.1% under $N_{60\%}$ and $N_{100\%}$ compared to the N_0, respectively. N fertilizer rate significantly influenced the spike number irrespective of supplemental drip irrigation times (Table 3). Grain yield and yield component of wheat were significantly affected by supplemental drip irrigation time and N fertilizer rate (Table 3). The interaction of supplemental drip irrigation time and N fertilizer rate had significant effects on the 1000-grain weight of wheat (Table 3). CK significantly produced 10.0%, 9.5% and 9.6% lower wheat yield compared to $DI_5N_{60\%}$, $DI_5N_{100\%}$ and $DI_5N_{140\%}$ in 2015–2016, respectively, while which significantly increase wheat yield by 50.2% and 27.4% compared to $DI_5N_{60\%}$ and $DI_5N_{100\%}$ in 2018–2019, respectively (Supplementary Fig. S1).

For maize, grain yield was significantly higher by 47.9% under DI_3 as compared to DI_0 treatment, but it was on a par with DI_5 (Table 3). Significant increase in ear number, kernel number per ear and 1000 kernel weight were observed by 10.1%, 5.6% and 25.8% under DI_3 as compared to the no irrigation but was on a par with DI_5 (Table 3). Grain yield was 8.1% and 17.1% significantly higher under $N_{60\%}$ and $N_{100\%}$ compared to N_0 treatment (5895.6 kg ha^{-1}), respectively (Table 3). Supplemental drip irrigation time as well as N fertilizer rate showed significantly influence on grain yield. Unlike wheat, N fertilizer rate showed no significant effect on the ear number and kernel number per ear of maize (Table 3). The interaction of supplemental drip irrigation time and N fertilizer rate had significant effects on the ear number of maize. No significant differences in maize yield were observed between CK and drip fertigated treatments, except of $DI_3N_{100\%}$ in 2018 and $DI_5N_{100\%}$ in 2019 (Supplementary Fig. S2).

3.2. Evapotranspiration and water use efficiency

ET_a for wheat under DI_0 (308 mm) was 57 mm and 72 mm significantly lesser compared with DI_3 and DI_5, respectively (Table 4). ET_a for maize under DI_3 and DI_5 was 38 mm and 34 mm significantly higher compared to the DI_0 (219 mm), respectively (Table 4). N fertilizer rate showed no significant effect on ET_a for both wheat and maize. The

Table 4
Effects of supplemental drip irrigation time and nitrogen (N) fertilizer rate on evapotranspiration (ET_a) and water use efficiency (WUE) of winter wheat and summer maize.

Treatments	Winter wheat		Summer maize	
	ET_a (mm)	WUE (kg m^{-3})	ET_a (mm)	WUE (kg m^{-3})
Supplemental drip irrigation time (DI)				
DI_0	308b	1.93a	219b	2.31b
DI_3	365a	1.94a	257a	2.83a
DI_5	380a	1.89a	253a	2.97a
N rate (kg ha^{-1})				
N_0	357a	1.67c	238a	2.51a
$N_{60\%}$	355a	1.97b	237a	2.78a
$N_{100\%}$	341a	2.13a	254a	2.83a
Year				
2016–2017	329b	2.68a	217b	3.07a
2017–2018	342b	1.56b	234b	2.93a
2018–2019	382a	1.53b	278a	2.12b
ANOVA (Pr > F)				
DI	***	NS	**	**
N rate	NS	***	NS	NS
Year	***	***	***	***
DI×N rate	*	*	NS	**
DI×Year	*	***	*	NS
N rate×Year	NS	*	NS	*
DI×N rate×Year	NS	NS	NS	NS

Note: *, ** and *** means significant at the P = 0.05, P = 0.01 and P = 0.001 levels, respectively. NS means non-significant at the P = 0.05 level. Values in a column not followed by same letter (s) differ significantly at the P = 0.05 level. DI_0 indicates no irrigation after emergence; DI_3 indicates irrigation once at wheat jointing, once at maize seedling and once at maize jointing; DI_5 indicates irrigation once at wheat jointing, once at wheat anthesis, once at maize seedling, once at maize jointing and once at maize tasseling; N_0, $N_{60\%}$ and $N_{100\%}$ represent 0, 60% and 100% of local recommended N fertilizer rate, respectively.

Table 3
Effects of supplemental drip irrigation time and nitrogen (N) fertilizer rate on yield and yield component of winter wheat and summer maize.

Treatments	Winter wheat				Summer maize			
	Grain yield (kg ha^{-1})	Spike number (10^4 ha^{-1})	Kernels per spike	1000-grain weight (g)	Grain yield (kg ha^{-1})	Ear number (10^3 ha^{-1})	Kernels per ear	1000-kernel weight (g)
Supplemental drip irrigation time (DI)								
DI_0	5753.7b	518.54b	28.81b	44.84b	4830.7b	45.03b	539.11b	267.77b
DI_3	6955.8a	594.14a	31.92a	44.75b	7147.0a	49.59a	569.31a	336.76a
DI_5	7003.5a	588.09a	31.46a	46.71a	7191.8a	48.63a	567.61a	335.26a
N rate (kg ha^{-1})								
N_0	5756.0b	526.20c	29.14b	44.51b	5895.6c	46.92a	559.90a	305.17a
$N_{60\%}$	6814.7a	566.10b	31.58a	46.16a	6371.6ab	47.56a	558.63a	319.77a
$N_{100\%}$	7142.4a	608.47a	31.48a	45.63ab	6902.2a	48.60a	557.50a	314.85a
Year								
2016–2017	8746.7a	637.03a	32.62a	45.16a	6420.5ab	48.58a	516.53c	338.64a
2017–2018	5179.3c	494.56c	28.57b	45.67a	6801.0a	47.90ab	564.54b	327.28a
2018–2019	5787.0b	569.18b	31.01a	45.48a	5947.9b	46.61b	594.95a	273.87b
ANOVA (Pr > F)								
DI	***	***	**	***	***	***	**	***
N rate	***	***	**	***	***	NS	NS	***
Year	***	***	***	NS	**	NS	***	***
DI×N rate	NS	NS	NS	**	NS	**	NS	NS
DI×Year	**	*	NS	***	***	NS	**	***
N rate×Year	**	NS	NS	**	*	*	NS	***
DI×N rate×Year	NS	NS	NS	*	NS	NS	NS	**

Note: *, ** and *** means significant at the P = 0.05, P = 0.01 and P = 0.001 levels, respectively. NS means non-significant at the P = 0.05 level. Values in a column not followed by same letter (s) differ significantly at the P = 0.05 level. DI_0 indicates no irrigation after emergence; DI_3 indicates irrigation once at wheat jointing, once at maize seedling and once at maize jointing; DI_5 indicates irrigation once at wheat jointing, once at wheat anthesis, once at maize seedling, once at maize jointing and once at maize tasseling; N_0, $N_{60\%}$ and $N_{100\%}$ represent 0, 60% and 100% of local recommended N fertilizer rate, respectively.

interaction of supplemental drip irrigation time and N fertilizer rate had significant effects on the ET_a for wheat (Table 4). For wheat, compared to CK, $DI_3N_{100\%}$ significantly decreased ET_a by 41–132 mm in all the four seasons, $DI_3N_{60\%}$ and $DI_5N_{100\%}$ significantly decreased ET_a by 79–125 mm and 80–123 mm, respectively in the last three seasons and $DI_3N_{140\%}$ significantly decreased ET_a by 53 mm in the first season (Supplementary Table S1). For maize, $DI_5N_{60\%}$ significantly decreased ET_a by 96 mm compared to CK in 2017 (Supplementary Table S1).

WUE ranged from 1.05 to 3.05 kg m^{-3} and 1.29–3.91 kg m^{-3} for wheat and maize, respectively (Supplementary Table S1). Supplemental drip irrigation time showed no significant effect on WUE in wheat (Table 4). In maize, WUE under DI_3 and DI_5 was significantly higher by 22.5% and 28.6% compared to the DI_0 (2.31 kg m^{-3}), respectively (Table 4). WUE in wheat increased significantly with increasing N fertilizer rate, which under $N_{100\%}$ (2.13 kg m^{-3}) was significantly higher by 18.0% and 27.5% compared to the $N_{60\%}$ and N_0, respectively (Table 4). N fertilizer rate showed no significant effect on WUE in maize (Table 4). The interaction of supplemental drip irrigation time and N fertilizer rate had significant effects on the WUE for both wheat and maize. The average WUE in wheat and maize under $DI_5N_{60\%}$ was 1.93 kg m^{-3} and 3.00 kg m^{-3}, which was 3.0% and 25.3% higher compared to CK, respectively (Supplementary Table S1).

3.3. Soil nitrogen loss and nitrogen use efficiencies

The soil N budget of winter wheat-summer maize for the three whole growth period during 2016–2019 was calculated (Fig. 2). Generally, N losses decreased with the decrease of N fertilizer rate. $DI_3N_{60\%}$ and $DI_5N_{60\%}$ significantly reduced N losses by 610 kg N ha^{-1} and 685 kg N ha^{-1} compared to CK, respectively.

For wheat, supplemental drip irrigation time showed significant effects on RE_N, AE_N and PEP_N (Table 5). The AE_N and PEP_N under DI_3 was significantly higher by 63.3% and 22.8% as compared to the DI_0 treatment, respectively, while which was no significant difference compared to DI_5. RE_N and PEP_N was maximum under $N_{60\%}$, which decreased significantly under $N_{100\%}$ (Table 5). N fertilizer rate did not influence AE_N. On average, the highest PEP_N was observed in $DI_5N_{60\%}$ (56.8 kg kg^{-1}), which was 3.7%, 63.9%, 61.3% and 54.0% higher compared to $DI_3N_{60\%}$, $DI_3N_{100\%}$, $DI_5N_{100\%}$ and CK, respectively (Supplementary Table S1).

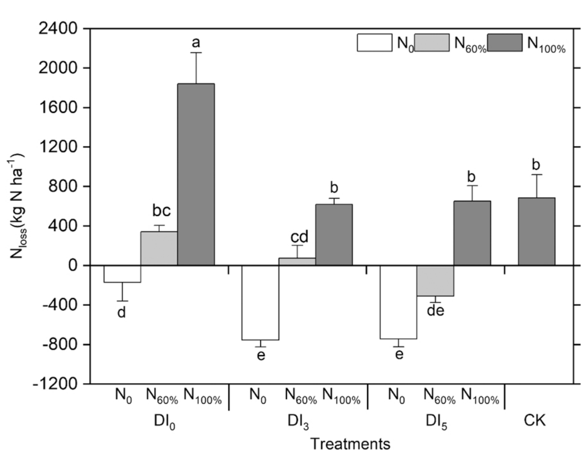

Fig. 2. Nitrogen losses of winter wheat-summer maize double cropping system during 2016–2019 under different irrigation and nitrogen managements. Values are means. Error bars represent standard errors. Different lowercase letters indicate statistically significant differences at the P = 0.05 level. DI_0 indicates no irrigation after emergence; DI_3 indicates irrigation once at wheat jointing, once at maize seedling and once at maize jointing; DI_5 indicates irrigation once at wheat jointing, once at wheat anthesis, once at maize seedling, once at maize jointing and once at maize tasseling; N_0, $N_{60\%}$, $N_{100\%}$ and $N_{140\%}$ represent 0, 60%, 100% and 140% of local recommended N fertilizer rate, respectively. CK represents traditional surface irrigation method under 100% of local recommended N fertilizer rate at 453 kg N ha^{-1} yr^{-1}.

Table 5
Effects of supplemental drip irrigation time and nitrogen (N) fertilizer rate on recovery efficiency (RE_N), agronomic efficiency (AE_N) and partial factor productivity from applied N (PFP_N) of winter wheat and summer maize.

Treatments	Winter wheat			Summer maize		
	RE_N (kg kg^{-1})	AE_N (kg kg^{-1})	PEP_N (kg kg^{-1})	RE_N (kg kg^{-1})	AE_N (kg kg^{-1})	PEP_N (kg kg^{-1})
Supplemental drip irrigation time (DI)						
DI_0	0.26b	4.93b	35.14b	0.09b	4.77a	29.28b
DI_3	0.32ab	8.05a	43.16a	0.23a	5.58a	43.73a
DI_5	0.51a	7.74a	43.33a	0.33a	5.68a	43.79a
N rate (kg ha^{-1})						
$N_{60\%}$	0.46a	7.73a	49.75a	0.27a	5.62a	47.19a
$N_{100\%}$	0.27b	6.09a	31.33b	0.16a	5.06a	30.68b
Year						
2016–2017	0.36a	3.72b	52.22a	0.32a	8.66a	40.65a
2017–2018	0.42a	10.97a	35.54b	0.09b	3.41b	40.44a
2018–2019	0.32a	6.04b	33.87b	0.23a	3.96b	35.72b
ANOVA (Pr > F)						
DI	**	*	***	**	NS	***
N rate	**	NS	***	NS	NS	***
Year	NS	***	***	**	***	**
DI×N rate	NS	NS	NS	NS	*	**
DI×Year	***	*	*	NS	*	**
N rate×Year	*	NS	**	NS	NS	NS
DI×N rate×Year	NS	NS	NS	NS	NS	NS

Note: *, ** and *** means significant at the P = 0.05, P = 0.01 and P = 0.001 levels, respectively. NS means non-significant at the P = 0.05 level. Values in a column not followed by same letter (s) differ significantly at the P = 0.05 level. DI_0 indicates no irrigation after emergence; DI_3 indicates irrigation once at wheat jointing, once at maize seedling and once at maize jointing; DI_5 indicates irrigation once at wheat jointing, once at wheat anthesis, once at maize seedling, once at maize jointing; and once at maize tasseling; N_0, $N_{60\%}$ and $N_{100\%}$ represent 0, 60% and 100% of local recommended N fertilizer rate, respectively.

For maize, supplemental drip irrigation time showed significant influences on RE_N and PEP_N (Table 5). The RE_N and PEP_N under DI_3 was significantly higher by 0.14 kg kg^{-1} and 14.15 kg kg^{-1} as compared to DI_0 treatment, respectively, but which was no significant compared to DI_5. N fertilizer rate showed significant effect on PEP_N in maize only (Table 5). Like wheat, $N_{60\%}$ gave about 53.8% higher PEP_N as compared to $N_{100\%}$. The interaction of supplemental drip irrigation time and N fertilizer rate had significant effects on both AE_N and PEP_N. On average, the highest PEP_N was observed in $DI_5N_{60\%}$ (56.3 kg kg^{-1}), which was 61.3%, 60.5% and 74.0% higher compared to $DI_3N_{100\%}$, $DI_5N_{100\%}$ and CK, respectively (Supplementary Table S1).

3.4. Economic benefit

Total cost in wheat increased significantly with increasing supplemental drip irrigation time and N fertilizer rate, and the similar trend in maize was also observed (Table 6). Drip irrigated treatments significantly increased gross profit compared to no irrigation for both the crops (Table 6). For wheat, net income recorded under DI_3 was 11.9% higher compared to DI_0, but was on par with DI_5 (Table 6). N fertilized treatments resulted in significantly higher valued of net income compared to no N control but the increase with $N_{60\%}$ and $N_{100\%}$ was similar (Table 6). Unlike wheat, N fertilizer rate showed no significant effect on net income in maize. DI_3 treatment was at par with DI_5 in increasing net income in maize. The interaction of supplemental drip irrigation time and N fertilizer rate had no significant effects on net income for both the crops. $DI_5N_{60\%}$ significantly increased net income of wheat by 12.0% over CK in 2015–2016 but performed no significance in 2016–2017 and 2017–2018 (Supplementary Fig. S3). Net income of maize was not

Table 6
Effects of supplemental drip irrigation time and nitrogen (N) fertilizer rate on economic benefits of winter wheat and summer maize.

Treatments	Winter Wheat			Summer maize		
	Total cost (CNY ha^{-1})	Gross profit (CNY ha^{-1})	Net income (CNY ha^{-1})	Total cost (CNY ha^{-1})	Gross profit (CNY ha^{-1})	Net income (CNY ha^{-1})
Supplemental drip irrigation time (DI)						
DI_0	5963.7c	13,697.0b	7733.4b	4833.0c	8463.8b	3630.8b
DI_3	7879.8b	16,532.5a	8652.7a	6801.9b	12,662.9a	5861.0a
DI_5	8278.1a	16,671.5a	8392.9ab	7144.2a	12,747.6a	5603.4a
N rate (kg ha^{-1})						
N_0	6421.5c	13,707.8b	7286.4b	5511.8c	10,447.2b	4935.4a
$N_{60\%}$	7497.9b	16,213.0a	8715.2a	6365.8b	11,248.5ab	4882.6a
$N_{100\%}$	8202.8a	16,980.1a	8777.3a	6901.5a	12,178.6a	5277.1a
Year						
2016–2017	7316.3b	21,336.8a	14,020.5a	6012.5c	10,627.2b	4614.7b
2017–2018	7204.9c	12,324.7c	5119.8b	6228.3b	12,160.1a	5931.8a
2018–2019	7600.9a	13,239.6b	5638.6b	6538.3a	11,086.9b	4548.6b
ANOVA (Pr > F)						
DI	***	***	*	***	***	***
N rate	***	***	***	***	***	NS
Year	***	***	***	**	***	**
DI×N rate	***	NS	NS	***	NS	NS
DI×Year	***	**	**	***	***	***
N rate×Year	***	**	**	***	*	*
DI×N rate×Year	*	NS	NS	*	NS	NS

Note: *, ** and *** means significant at the P = 0.05, P = 0.01 and P = 0.001 levels, respectively. NS means non-significant at the P = 0.05 level. Values in a column not followed by same letter (s) differ significantly at the P = 0.05 level. DI_0 indicates no irrigation after emergence; DI_3 indicates irrigation once at wheat jointing, once at maize seedling and once at maize jointing; DI_5 indicates irrigation once at wheat jointing, once at wheat anthesis, once at maize seedling, once at maize jointing and once at maize tasseling; N_0, $N_{60\%}$ and $N_{100\%}$ represent 0, 60% and 100% of local recommended N fertilizer rate, respectively. Calculation basis of the detailed expenses: the cost of main equipment (including mainlines, submain lines, laterals, drippers, fertilizer pump and others) of field drip fertigation system was 11,225 CNY ha^{-1} and the economic life was 3 years (6 seasons), therefore, the cost of drip fertigation system was 1870 CNY ha^{-1} per season; the cost of mechanical energy for wheat and maize was about 2000 CNY ha^{-1} and 1800 CNY ha^{-1}, respectively; the prices of seeds, herbicides, pesticides, fertilizers, water, labor expenditures and sales price of grains were used according to the Hebei Rural Statistical Year book. 1 CNY was approximately equal to 0.15 USD during the study period.

significantly higher in CK compared with $DI_3N_{60\%}$ and DI_5 treatments, irrespective of $N_{60\%}$ and $N_{100\%}$ (Supplementary Fig. S4). The average net income in $DI_5N_{60\%}$ was 17,887 CNY ha^{-1} for winter wheat-summer maize double cropping system, which was on a par with CK (17,898 CNY ha^{-1}).

3.5. *Optimized irrigation and nitrogen fertilizer inputs*

Response variables of yield, WUE, PFP_N and net income of wheat and maize under different irrigation amount and N fertilizer rate fits the binary quadratic regression equations with highly significant (Table 7). When the crop yield, WUE and net income achieved their maxima, the amounts of irrigation and N fertilizer needed for each were similar, but the values needed to maximize the PFP_N were significantly different (Figs. 3 and 4). Therefore, it was difficult to identify the overlap between PEP_N and crop yield, WUE and net income due to the opposing trends of PFP_N. Without regard to PEP_N, when the irrigation was approximate 165 mm and the N fertilizer was approximate 186 kg N ha^{-1} for wheat, 70%, 60% and 70% of the maximum yield, WUE and net income were overlapped, which were considered as producing optimal yield, WUE and net income simultaneously (Fig. 5a). Likewise, when irrigation was approximate 90 mm and the N fertilizer was approximate 185 kg N ha^{-1} for maize, 90%, 80% and 80% of the maximum yield, WUE and net income were overlapped, reaching their optimal values simultaneously (Fig. 5b).

Table 7
Regression equations for the response variables of yield, water use efficiency (WUE), partial factor productivity from applied N (PFP_N) and net income of winter wheat and summer maize under different irrigation amounts and N fertilizer rates.

Crop	Response variable	Regression equation	R^2
Winter wheat	Yield (kg ha^{-1})	$y = 3699.60229 + 7.36503x_1 + 0.01973 \times_1^2 + 11.67851x_2 - 0.01453 \times_2^2$	0.525^{***}
	WUE (kg m^{-3})	$y = 1.23791 – 0.000795x_1 - 0.00000938 \times_1^2 + 0.00365x_2 - 0.00000345 \times_2^2$	0.357^{**}
	PEP_N (kg kg^{-1})	$y = 83.75025 + 0.0517x_1 + 0.0000481 \times_1^2 - 0.4037x_2 + 0.00059238 \times_2^2$	0.683^{***}
	Net income (CNY ha^{-1})	$y = 4100.39784 + 38.17199x_1 - 0.02014 \times_1^2 + 11.47654x_2 - 0.02224 \times_2^2$	0.252^{***}
Summer maize	Yield (kg ha^{-1})	$y = 3918.55994 + 50.86515x_1 - 0.245 \times_1^2 + 4.00864x_2 + 0.00997 \times_2^2$	0.605^{***}
	WUE (kg m^{-3})	$y = 1.86481 + 0.00481x_1 + 0.0000199 \times_1^2 + 0.00214x_2 - 0.00000231 \times_2^2$	0.274^{**}
	PEP_N (kg kg^{-1})	$y = 79.55293 + 0.24072x_1 - 0.00116 \times_1^2 - 0.39159x_2 + 0.000619 \times_2^2$	0.586^{***}
	Net income (CNY ha^{-1})	$y = 4655.5958 + 89.79893x_1 - 0.5799 \times_1^2 + 1.84444x_2 + 0.0001171 \times_2^2$	0.402^{***}

Note: x_1 refers to irrigation amount (mm) and x_2 refers to N fertilizer rate (kg N ha^{-1}). ** and *** means significant at the P = 0.01 and P = 0.001 levels, respectively. Net income denotes gross profit substrates total cost.

4. Discussion

4.1. *Grain yield, WUE and NUE responses*

Grain yields of both wheat and maize were significantly affected by supplemental drip irrigation time (Table 3), which is consistent with findings showing yield advantages of irrigation conditions compared to no irrigation under sprinkling and surface irrigation methods (Wang et al., 2014; Xu et al., 2018). The significant increases in grain yields of wheat and maize under irrigation conditions in comparison to no irrigation were attributed to increase in yield components such as spike number and kernels per spike in wheat and ear number, kernels per ear and 1000-kernel weight in maize (Table 3). The similar result was also concluded by Wang et al. (2013), who reported that the effects of

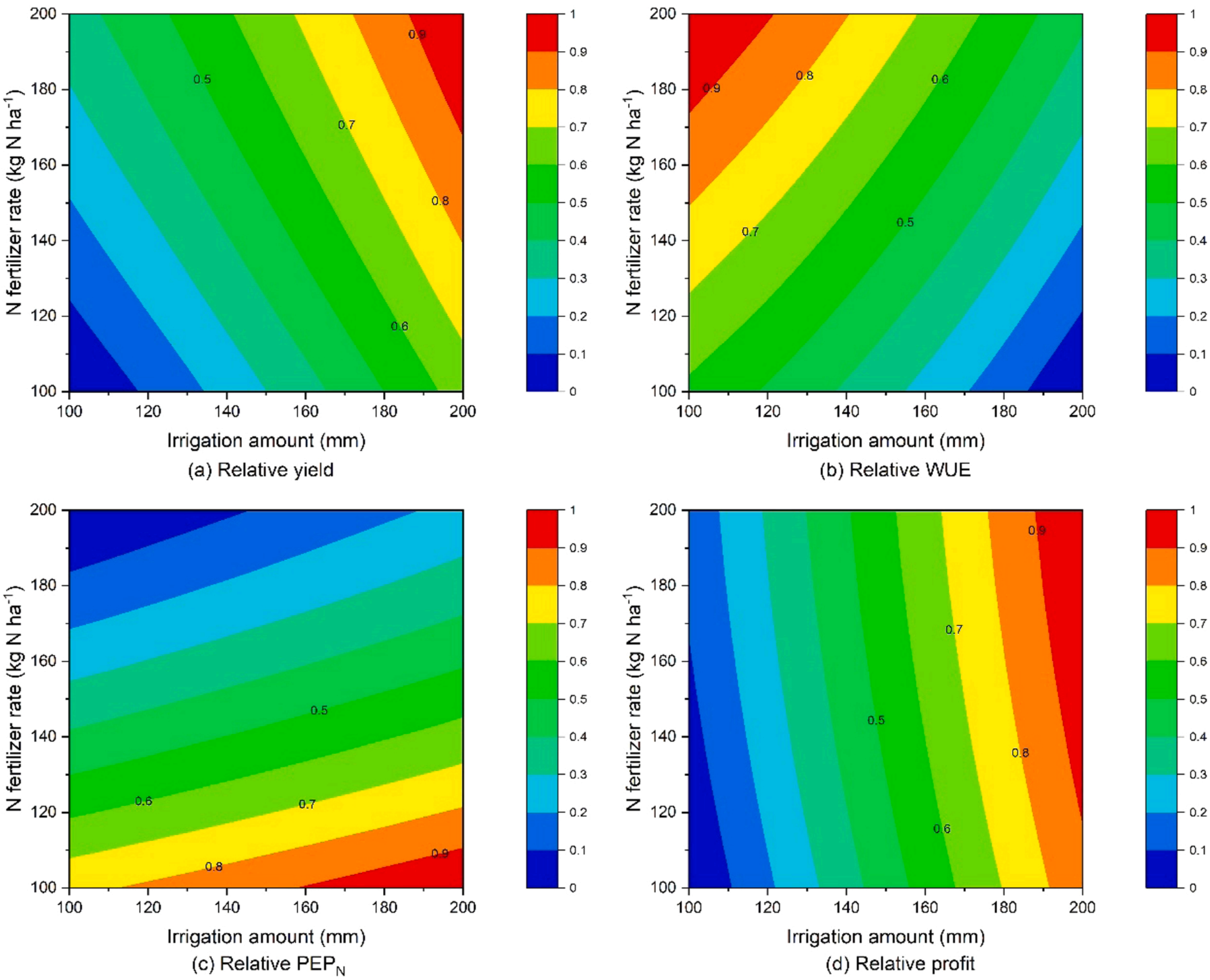

Fig. 3. Response surfaces for relative yield (a), relative WUE (b), relative PEP_N (c) and relative profit (d) under irrigation amount and N fertilizer rate of winter wheat. WUE denotes water use efficiency, PEP_N denotes partial factor productivity from applied N. Net income denotes gross profit substrates total cost. 0.9, 0.8, 0.7, 0.6 and 0.5 denote ratio of each index of its maximum value. Relative yield, relative WUE, relative PEP_N and relative net income are the values between 0 and 1 after normalizing for yield, WUE, PEP_N and net income, respectively.

supplemental irrigation on grain yield were through the coordination of yield components. It is rather remarkable that there were no significant differences in spike number or kernel numbers per spike in wheat between DI_3 and DI_5, but DI_5 resulted in significantly higher 1000-grain weight of 4.4% compared to DI_3 (Table 3). This result revealed that irrigation at anthesis stage might be beneficial to the rate and duration of the grain filling further improve wheat grain yield and this is consistent with the previous findings conducted in the NCP (Wang et al., 2013; Zhang et al., 2019). The further reason for increasing yield in DI_5 might be due to providing favorable soil moisture in jointing and anthesis stage is conducive to coordinating the pre- and post-anthesis water consumption, optimize the canopy structure and ensure wheat physiological water demand post-anthesis (Oweis et al., 2000; Xu et al., 2018; Zhang et al., 2019). The significant increase in grain yield with the N fertigated conditions over no N control in both the crops was due to better supply of N at the critical growth periods in the mainly root system distribution zone, which was beneficial to increase grain yield (Li et al., 2019a). Notably wheat, the spike number was significantly increased with increasing N rate (Table 3), indicating supply appropriate N can ensure the more tillers and spikes.

The grain yield of wheat under DI_5 fertilized treatments showed no significant decrease compared to CK irrespective of N fertilizer rate only about 20% significant lower in 2018–2019 (Supplementary Fig. S1). Unlike wheat, both DI_3 and DI_5 fertilized treatments obtained similar even higher yield in maize compared to CK (Supplementary Fig. S1). These results indicated that supplemental irrigation is more important for wheat than maize due to the limited water supply conditions. Meanwhile, our results showed that under drip fertigation, 40% reduction of N recommended rate did not influence the grain yield of both wheat and maize (Table 3). These similar results were also concluded by Li et al. (2019a) and Bai et al. (2020). The reason for these results is that drip fertigation can simultaneously transport N fertilizer and water to the vicinity of active roots, which improve NUE consequently apply less N fertilizer to ensure the grain yield (Silber et al., 2002; Abd El-Wahed and Ali, 2013). In addition, the great yield variation in these seasons might be due to the differences in sowing time, harvesting time and weather conditions. For winter wheat, the sowing date in 2017 was late (22th October) due to the rainfall pre-sowing and the tillers was fewer caused by insufficient accumulated temperature, eventually resulting in the significant lower spikes at maturity. The early sowing date in 2018 (8th October) may cause the spike differentiation in advance, which is easier to suffer freezing damage due to the continuous low temperature in the middle and late December 2018 (the lowest temperature reached −9 °C). For summer maize, early harvesting in 2018 may result in a foreshortened grain-filling period, which had a negative effect on grain yield. The relative lower yield of maize in 2019 might be due to the abundant precipitation in tasseling stage counteracted for the beneficial of fertigation.

The increase in WUE is the resultant of both increase in yield and decrease in crop evapotranspiration. Our results showed that the higher

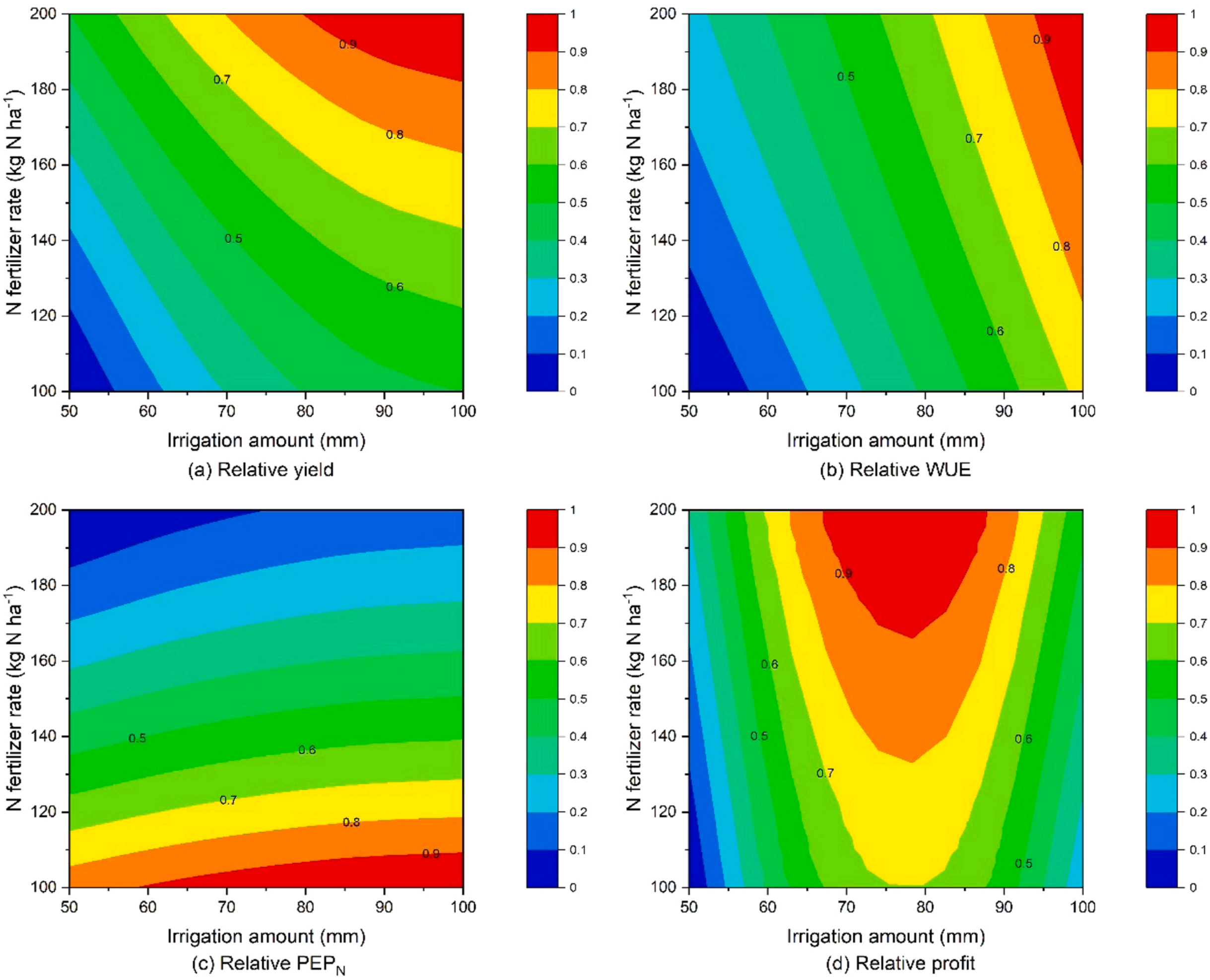

Fig. 4. Response surfaces for relative yield (a), relative WUE (b), relative PEP_N (c) and relative profit (d) under irrigation amount and N fertilizer rate of summer maize. WUE denotes water use efficiency, PEP_N denotes partial factor productivity from applied N. Net income denotes gross profit substrates total cost. 0.9, 0.8, 0.7, 0.6 and 0.5 denote ratio of each index of its maximum value. Relative yield, relative WUE, relative PEP_N and relative net income are the values between 0 and 1 after normalizing for yield, WUE, PEP_N and net income, respectively.

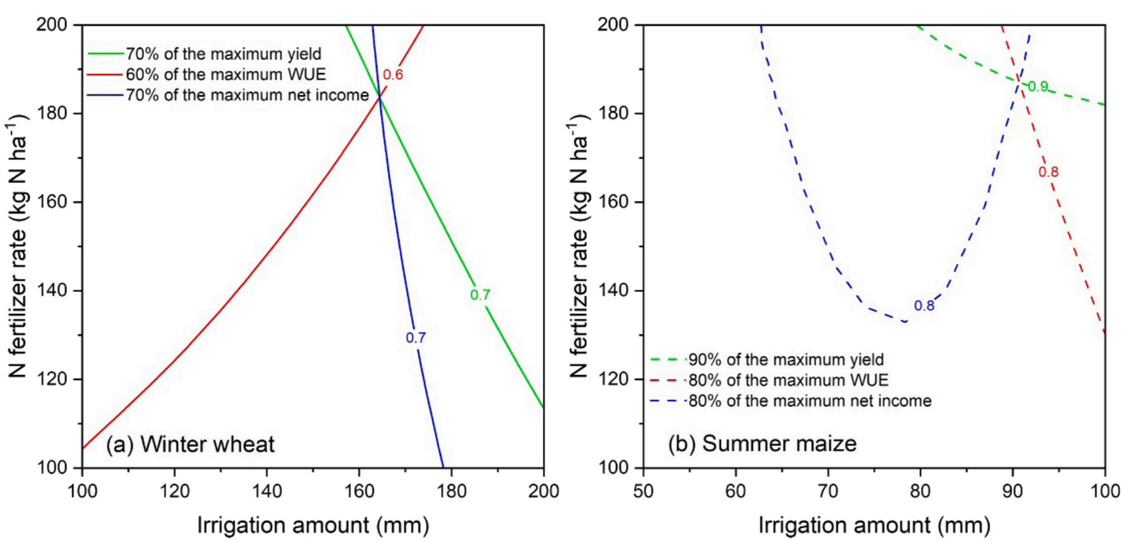

Fig. 5. Comprehensive evaluation of yield, WUE and net income for winter wheat (a) and summer maize (b). WUE denotes water use efficiency. Net income denotes gross profit substrates total cost. The green, red and blue solid line represents 70%, 60% and 70% of the maximum yield, WUE and net income in wheat, respectively. The green, red and blue dash line represents 90%, 80% and 80% of the maximum yield, WUE and net income in maize, respectively.

WUEs in wheat and maize were observed in drip irrigation as compared to the surface irrigation irrespective of supplemental drip irrigation times (Supplementary Table S1), which is in accordance with the previous studies (Jha et al., 2019). The reason for these results was mainly due to reduction in irrigation percolation by apply water directly to the root zone but ensuring the similar yield under drip irrigation. The improvement in PEP_N of wheat and maize in $N_{60\%}$ irrespective of supplemental drip irrigation times in comparison to CK (Supplementary Table S1) was attributed to increase in yield and decrease in N fertilizer rate. A similar trend was observed in N loss, that is, $N_{60\%}$ significantly reduced N loss irrespective of supplemental drip irrigation times compared to CK. However, no significant decrease was observed in $N_{100\%}$ compared to CK irrespective of supplemental drip irrigation times (Fig. 2), which was inconsistent with Wu et al. (2019), who concluded that under the same N application rate, drip fertigation reduced N loss at greater extent than conventional treatments. The reason for the different results might be due to the supplemental drip irrigation only at wheat jointing and anthesis stage is insufficient to affecting the N balance during the whole growing season. It is noteworthy that the N loss in $DI_0N_{100\%}$ was significant higher compared to other treatments (Fig. 2). The reason might be due to non-irrigation reduced plant N uptake availability. The negative N in the N_0 treatment may be attributed to biological N_2 fixation, N deposition, mineralization of soil organic N and possibly other processes (Chen et al., 2021), and the source of N in N_0 may come from free-living, endophytic biological N_2 fixation, N deposition, etc. (Xu et al., 2015; Ladha et al., 2016). All these above results indicated that reducing N fertilizer rate is pivotal for sustainable agriculture. The similar result was also concluded by Bai et al. (2020), who reported that 30% N reduction with drip fertigation was suggested in the NCP to achieve a relatively high grain yield, high fertilization use efficiency, and minimize risk of environment pollution. The benefit of drip fertigation in winter wheat-summer maize system was also proved by the previous studies conducted in the other parts of the world, such as north-western India (Sandhu et al., 2019) and Iran (Afzalinia and Dehghanian, 2021).

4.2. Evaluation of optimal irrigation and N fertilizer inputs

Crop yield alone is not enough to determine the optimal irrigation and fertilization amount, WUE, NUE and the economic profit must be considered from a long-term point of view. In recent years, many researchers have established binary quadratic regression equations of crop yield, WUE, NUE and economic profit with irrigation and fertilization in spring maize and cotton in Northwest China (Wang et al., 2018; Zou et al., 2020; Yan et al., 2021), rarely studied on wheat and maize in the NCP. The relationship of yield, WUE, PEP_N and net income with irrigation and N fertilizer amount of winter wheat and summer maize were established in this study. Our results showed that the optimal irrigation amount were 165 mm and 90 mm, and N rates were 186 kg N ha^{-1} and 185 kg N ha^{-1} for winter wheat and summer maize, respectively (Fig. 5). This result was consistent with Lu et al. (2021), who suggested that the N application rates were 165–211 kg N ha^{-1} and 187–250 kg N ha^{-1} for winter wheat and summer maize, respectively in Northwest China. Similar N fertilizer amount were also reported by Wang et al. (2017) and Zhang et al. (2017), who also suggested that the optimal N fertilizer rate for high grain yield of winter wheat in the NCP were 180–240 kg N ha^{-1}. Liu et al. (2003) suggested that the suitable N application for high grain yield of summer maize in the NCP was about 180 kg ha^{-1}. Li et al. (2021a) also reported that 180 kg N ha^{-1} applied by drip fertigation at the seven-leaf stage, ten-leaf stage and silking stage could increase the yield and reduce the environmental burden. Those previous studies can support our results that 186 kg N ha^{-1} for winter wheat and 185 kg N ha^{-1} for summer maize can obtain the similar annual grain yield compared to high local N recommended rate (228 kg N ha^{-1} for winter wheat and 225 kg N ha^{-1} for summer maize) without significant difference. There similar results were not only proved by other experimental studies, but also proved by model simulation. Zhao et al. (2015) combined field data with scenario modeling to optimize irrigation and N fertilizer input and concluded that 225 mm irrigation water and 330 kg N ha^{-1} (150 for wheat and 180 for maize) N fertilizer can obtain 18 t ha^{-1} grain yield with the minimum impact on the environment in winter wheat-summer maize double cropping system in the NCP. Li et al. (2019b) also showed that when the N fertilizer rate of winter wheat and summer maize exceeded 216 kg N ha^{-1} and 206 kg N ha^{-1}, respectively, increasing N inputs had little effect on crop yields, which were consistent with our results. However, Li et al. (2021b) suggested that the optimal irrigation amounts under drip fertigation for wheat and maize were 188 and 132 mm, respectively, and the optimal N fertilizer rates under drip fertigation for wheat and maize were 138 kg N ha^{-1} and 162 kg N ha^{-1}, respectively by using meta-analysis in China. The inconsistency with our results may be due to the crop varieties studied in Li et al. (2021b) including spring wheat and spring maize, which the N and water demand are different.

5. Conclusions

This study showed that supplemental drip fertigation is highly effective in terms of saving water and N fertilizer inputs, increasing WUE and NUE, and decreasing N loss over the traditional surface irrigation regime (CK) in winter wheat-summer maize double cropping system in the NCP. Supplemental drip irrigation at wheat jointing, wheat anthesis, maize seedling, maize jointing and maize tasseling (DI_5) with 40% reduction of local recommended N rate ($N_{60\%}$) is beneficial to achieve stable grain yield, improve WUE, NUE and net income and decrease N loss. The optimal irrigation amount and N fertilizer rate corresponding simultaneously to higher crop yield, WUE and net income were determined by using the response surface methodology. These results provide practical guidelines for sustainable production in winter wheat-summer maize double cropping system in semi-humid region.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The data that has been used is confidential.

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Appendix A. Supplementary material

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.agwat.2022.108053.

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