



## Article

# Efficient Irrigation Methods and Optimal Nitrogen Dose to Enhance Wheat Yield, Inputs Efficiency and Economic Benefits in the North China Plain

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**Abstract:** Nitrogen (N) and water irrigation are two vital factors influencing the agriculture sustainability in various regions across the world, such as the North China Plain (NCP). Exploring optimal N application and water-efficient irrigation methods are needed for achieving greater crop productivity benefits and increasing the efficiency of inputs (N and water) in winter wheat (*Triticum aestivum* L.) production in the NCP. For this reason, we conducted a two-year field experiment with four N application rates interacting with three irrigation methods to examine the effects of N fertilization and water-efficient irrigation on grain yield, biomass production, economic benefits, and N- and water-use efficiencies of winter wheat in the NCP. The optimal N fertilization rate was  $\approx 200$  kg N ha<sup>-1</sup>, achieving a high grain yield of winter wheat ( $\approx 6000$  kg ha<sup>-1</sup>). At this N dose, the highest net economic benefit was also achieved by the local farmer due to the increased grain yield, which was accompanied by more water-efficient irrigation. N recovery efficiency, agronomy efficiency, and the partial factor productivity of wheat decreased sharply with the N application rate. Water-use efficiency was significantly increased through drip irrigation and sprinkler irrigation. Considering the wheat productivity, input (N and water) efficiencies, and economic performance, water-efficient irrigation accompanied with an N application rate of 200 kg N ha<sup>-1</sup> is optimal for achieving high economic returns for local farmers in the NCP.

**Keywords:** grain yield; NUE; WUE; economic benefits; North China Plain



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## 1. Introduction

Rapid growth in the human population has led to an increasing need for cereal grain production across the world; however, meeting this demand requires the intensified use of chemical nitrogen (N) fertilizer and water resources [1,2]. In recent decades, cereal production has increased dramatically in China, primarily due to abundant N fertilizer application and sufficient irrigation [3]. Until now, crop production in China has consumed the largest amounts of N fertilizer and irrigation water globally [4,5]. However, sustainable agriculture development necessitates the optimization of N and irrigation management.

The North China Plain (NCP), characterized by rain-fed agriculture, is one of the most important agricultural production regions in China [6]. Winter wheat (*Triticum aestivum* L.) is a major crop in the NCP, and it provides more than 50% of the nation's wheat production [7]. The monsoon climate of the NCP features a disproportionate rainfall distribution; less than 30% of the annual precipitation falls in the winter wheat-growing

period (October to June the next year), which only meets 25–40% of winter wheat's water requirements [7–9]. For this reason, farmers rely heavily on irrigation to guarantee wheat yield; flood irrigation is common throughout this region [6,10,11]. However, flood irrigation requires large amounts of water and results in a low water-use efficiency (WUE), leading to serious water shortages, which threaten the sustainable development of agriculture in this region [7]. In recent years, water-efficient irrigation techniques (e.g., drip irrigation and sprinkler irrigation) that effectively conserve water have been substantially increased with government support [12,13]. Therefore, considering that the depth of groundwater has declined rapidly due to the excessive use of groundwater, research on optimizing irrigation WUE while maintaining, or even increasing, crop productivity is crucial for the sustainability of winter wheat production in the NCP.

N management in winter wheat is also a challenge in the NCP [4]. Excessive N fertilizer inputs are always favored by the local farmers because of favorable economic returns. For example, the average N fertilizer rate is usually more than 300 kg N ha<sup>−1</sup> for the winter wheat-growing season, which largely exceeds crop requirement in the NCP [14]; this is over 10 times that of the average N application rates in U.S. winter wheat production systems [15]. Although cereal crop yields have been growing slowly since the late 1980s, inputs of N fertilizer have continued to increase sharply on a national scale. On average, the total N inputs in China have increased more than twofold: from 9 million tons in the 1980s to approximately 20 million tons in 2019 [3]. Although grain yield always increases with N input, crop productivity can also decline with excessive N fertilizer application [16,17]. This over-application has resulted in wasted N fertilizer and low N-use efficiency (NUE), leading to environmental problems such as N-trace gas emissions (e.g., N<sub>2</sub>O, NO, and NH<sub>3</sub>) and nitrate pollution [18–20]. In addition to the environmental impacts of this excessive N application, the lack of yield gain at higher N fertilization rates is a wasted expense, which thus decreases a farmer's economic profits.

Crop yield can be enhanced significantly with appropriate N applications and water irrigation [2]. Therefore, to realize the sustainable development of wheat production and saving economic costs to farmers, there is an urgent need to optimize N application rates and explore water-efficient irrigation management for winter wheat production on a regional scale. Field studies over a wide range of N applications accompanied with water-efficient irrigation methods on winter wheat production are still lacking in the NCP.

In this study, we examined how winter wheat production and economic benefits respond to N fertilization and irrigation strategies. Our specific objectives were to (1) determine the main and interactive effects of N fertilizer on grain yield, biomass production, NUE, and WUE under different water-efficient irrigation methods; and (2) estimate the optimal N fertilization and irrigation methods for winter wheat production and economic benefits in the NCP.

## 2. Materials and Methods

### 2.1. Study Site

The field experiment was conducted on a local farm in Fengyang County (32°86' N, 117°4' E), which is located in the southern NCP. Winter wheat is the major cereal crop in this region, comprising more than 30% of arable land. This region is characterized by a sub-tropical and sub-humid monsoon climate, with an annual mean temperature of 15.2 °C. The annual mean precipitation is 1230 mm, although less than 40% of the rainfall occurs in the winter wheat-growing season. The soil physicochemical properties are shown in Table 1.

**Table 1.** Soil physicochemical properties in the top 20 cm layer.

|      | Soil Texture |          |          | pH  | Bulk Density       | Available N         | Organic C Content  |
|------|--------------|----------|----------|-----|--------------------|---------------------|--------------------|
|      | Sand (%)     | Silt (%) | Clay (%) |     | g cm <sup>−3</sup> | mg kg <sup>−1</sup> | g kg <sup>−1</sup> |
| Soil | 14           | 44       | 42       | 6.4 | 1.25               | 68.1                | 9.9                |

## 2.2. Experimental Design

The field experiment had a split-plot design. The main factor consisted of three irrigation methods, and the sub-factor consisted of four N fertilization rates. Thus, a total of twelve treatment combinations of N rate  $\times$  irrigation method were randomly arranged in an experimental unit, and each treatment had five replicates. Each plot was 4 m  $\times$  5 m in size, with a 0.5 m buffer zone between any two adjacent plots. The four N fertilization rates were 0 (N0), 100 (N-L), 200 (N-M), and 300 (N-H) kg N ha<sup>-1</sup> in the winter wheat-growing season. In accordance with the local farming practice, compound fertilizer (N:P<sub>2</sub>O<sub>5</sub>:K<sub>2</sub>O = 15%:15%:15%) as N fertilizer was applied with a 70% basal application (spread on the soil surface and then incorporated into the soil by ploughing before sowing) and a 30% top dressing at the wheat reviving stage. Irrigation methods, including conventional irrigation (flood irrigation) and two water-efficient irrigation methods (drip irrigation and sprinkler irrigation), were employed based on the soil moisture content of the field. The use of water in the three irrigation methods was controlled to supply the same amount.

The wheat cultivar 'Zhengmai 369', which is widely cultivated in this region, was sown with an average distance of 25 cm between two adjacent rows at a rate of 200 kg seeds ha<sup>-1</sup> on October 20 in 2018 and on October 18 in 2019.

## 2.3. Wheat Production Measurements

Five 1 m  $\times$  1 m quadrats in each plot were measured at wheat maturity (27 May 2019, and 2 June 2020, respectively) to calculate grain yields and biomass production. The grain yielded from each plot was collected in mesh bags. At the same time, wheat shoots and root samples were separated and collected for all treatments. Grain yields and plant biomass were oven-dried at 70 °C to constant weight for weighing. All the samples were ground to 0.5 mm and analyzed for N content to calculate the NUEs using the solid combustion method with an Elemental Analyzer (Elementar vario Macro cube, Elementar Co., Hanau, Germany).

## 2.4. Calculations of N- and Water-Use Efficiencies and Economic Benefits

NUEs were presented as recovery efficiency (RE<sub>N</sub>), agronomic efficiency (AE<sub>N</sub>), and partial factor productivity (PFP<sub>N</sub>).

RE<sub>N</sub>, considered as the nutrient supply of soil and fertilizer, can reflect the recycling degree of nitrogen fertilizer, and it is calculated as:

$$RE_N (\%) = (N_T - N_{CK}) / N_F \times 100 \quad (1)$$

where N<sub>T</sub> is the N content in the grain of the fertilized treatment, N<sub>CK</sub> is the N in the grain of the control treatment at harvest, and N<sub>F</sub> is the amount of N applied as fertilizer.

AE<sub>N</sub>, the increase in yield per unit of N application, can be evaluated by deducting the contribution of soil to crop yield, and it is calculated as:

$$AE_N (\text{kg kg}^{-1}) = (Y_T - Y_{CK}) / N_F \quad (2)$$

where Y<sub>T</sub> is the grain yield of the fertilized treatment, Y<sub>CK</sub> is the grain yield of the control treatment, and N<sub>F</sub> is the amount of N applied as fertilizer.

PFP<sub>N</sub> is the ratio of grain yield and N application rate, which shows the contribution of N application to crop yield, and it is calculated as:

$$PFP_N (\text{kg kg}^{-1}) = Y_T / N_F \quad (3)$$

where Y<sub>T</sub> is the grain yield and N<sub>F</sub> is the amount of N applied as fertilizer.

WUE at the crop yield level was estimated from the grain yield and water used by the crop [21]:

$$WUE (\text{kg ha}^{-1} \text{ mm}^{-1}) = \text{grain yield (kg ha}^{-1}) / \text{water used (mm)} \quad (4)$$

where the water used (mm) was calculated as the initial water content in the soil (mm) + precipitation (mm) + irrigation (mm) – soil water content at harvest (mm).

Economic benefits were expressed as the net economic income and ratio of output/input.

$$\text{Net economic income (CNY)} = \text{Output} - \text{Input} \quad (5)$$

where CNY is the Chinese currency (Yuan), output = grain yield  $\times$  price of wheat in each year, and input = the price of (N fertilizer + pesticide + wheat seed).

$$\text{Ratio of output/input} = \text{Output/input} \quad (6)$$

## 2.5. Statistical Analysis

The effect of time (year), N fertilization rate, irrigation method, and their interactions on grain yield, biomass production, and net economic income were determined using the SPSS software (SAS, 2013), with a repeated-measures option for the irrigation method. Differences in grain yield, wheat biomass, NUE, and WUE, as affected by N fertilizer, irrigation method, year, and their interactions, were examined using three-way analyses of variance (ANOVA). Linear or nonlinear regression analyses were conducted to examine the dependence of grain yield and plant biomass on N fertilization and irrigation. All the data are shown as the mean  $\pm$  SE ( $n = 5$ ). Calculations were performed with SPSS version 21.0 (SPSS Inc., Chicago, IL, USA), and statistical significance was determined at the 0.05 probability level.

## 3. Results

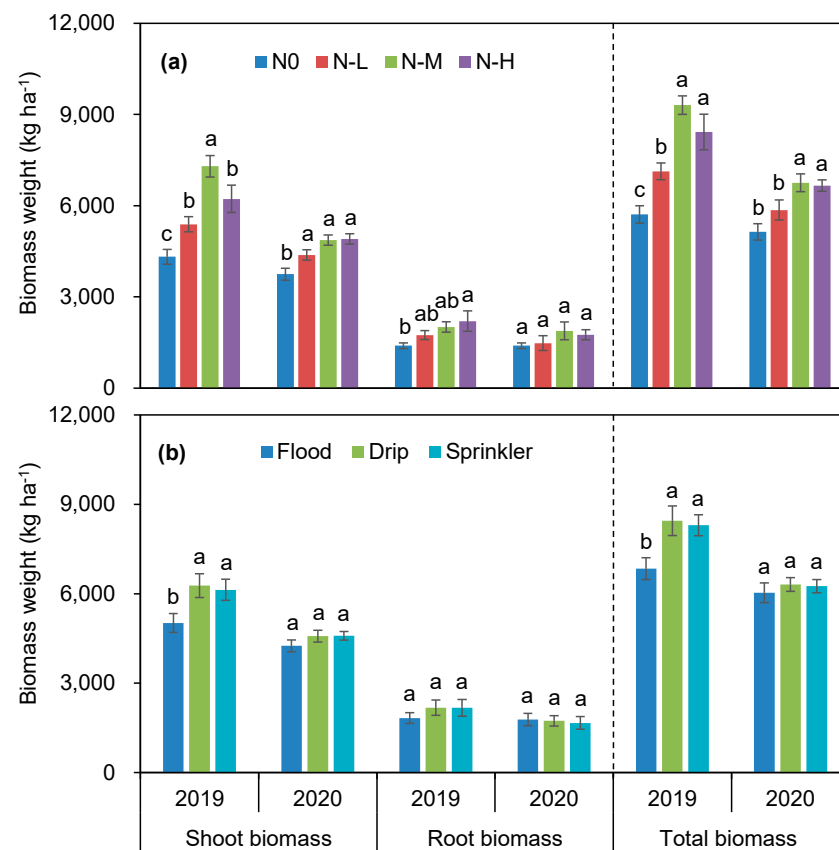
### 3.1. Biomass Production

Biomass production responded strongly to N fertilization and irrigation methods in both years (Figure 1, Table 2). Under different N application rates, shoot biomass ranged enormously: from 4318 to 6221 kg ha<sup>-1</sup> in 2019, which was greater than that in 2020 (3744 to 4903 kg ha<sup>-1</sup>). The highest shoot production occurred with 200 kg N ha<sup>-1</sup> and 300 kg N ha<sup>-1</sup> in 2019 and 2020, respectively. Although both N application and irrigation methods had significant effects on shoot production (except for irrigation methods in 2020), their interaction (N  $\times$  Ir) was not significant (Table 2). In contrast, root biomass showed no response to either N application (except for 2019) or irrigation methods, but they expressed a remarkable association with their interaction (N  $\times$  Ir). In general, the shoot, root, and total biomass showed significant quadratic relationships with the N application rate (Figure 2a–c).

### 3.2. Grain Yields

Grain yields were affected significantly by N application rates and water irrigation methods in both years, and they showed a notable yearly variation (Figure 3a,d, Table 2). Compared with the control, N-L, N-M, and N-H significantly enhanced the mean grain yields by 13.9%, 24.0%, and 20.6% during the two years, respectively. The highest grain yield was achieved at N-M treatment (200 kg N ha<sup>-1</sup>) in both years (5828.4 kg ha<sup>-1</sup> in 2019 and 6219 kg ha<sup>-1</sup> in 2020). Although N application in N-H treatment was 50% higher than N-M treatment, the grain yields were decreased by 5.1% in 2019 and 0.8% in 2020, suggesting that crop failure could be accompanied by excessive N application. N application significantly enhanced grain yield in both years. Generally, grain yields showed a strong quadratic relationship with N application rates, and the highest grain yield was achieved at an application rate of 200 kg N ha<sup>-1</sup> (Figure 2d).

For the irrigation method, although grain yields had no difference between drip and sprinkler irrigation, the two water-efficient irrigations significantly enhanced grain yields compared with flood irrigation in both years (Figure 3b). Relative to flood irrigation, drip irrigation and sprinkler irrigation significantly enhanced the mean grain yields by 8.8% and 11.1% during the two years, respectively.



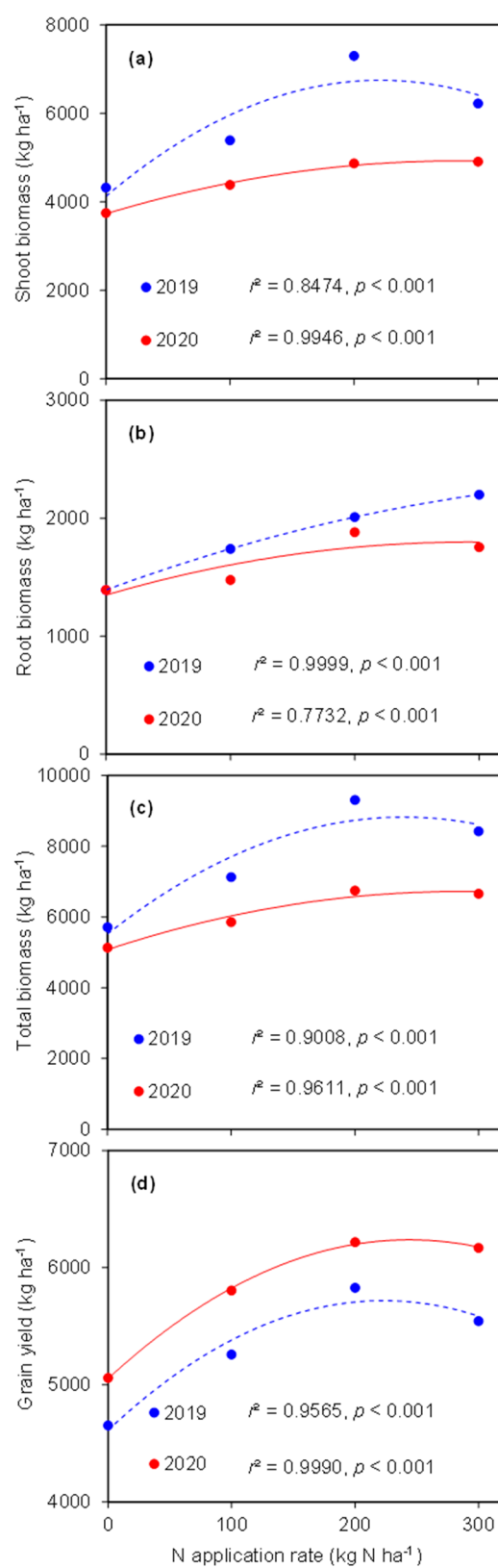
**Figure 1.** Biomass weight as affected by N application rates (a) and irrigation methods (b) during the two wheat-growing seasons in 2019 and 2020. The different letters above the bar indicate significant differences ( $p < 0.05$ ) according to the Fisher's LSD test.

### 3.3. Economic Benefits Assessment

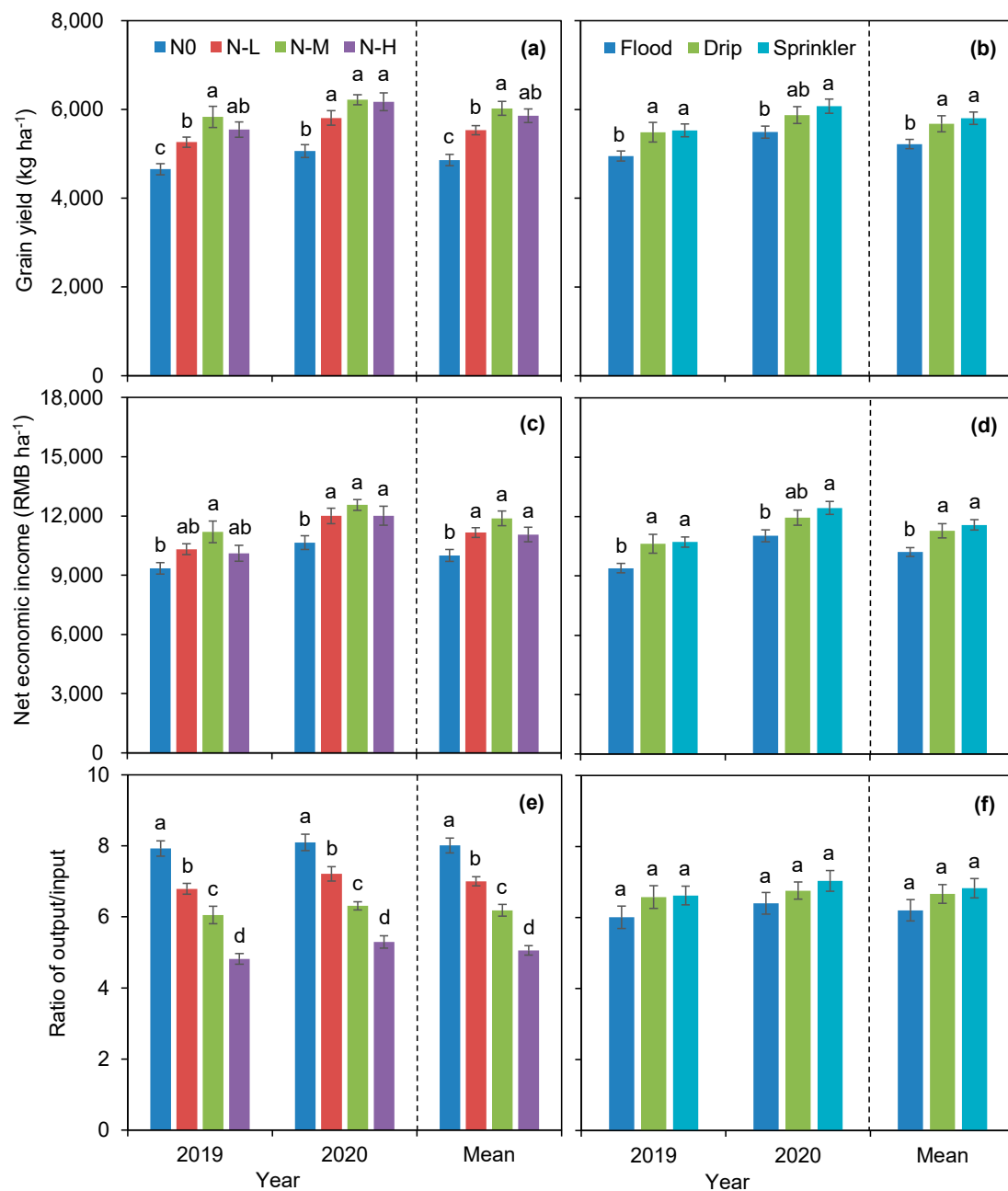
The net economic income and ratio of output/input were significantly influenced by N, irrigation, and their interaction during the two winter wheat seasons (Figure 3, Table 2). In agreement with grain yields, N application significantly enhanced grain yields and thus the net economic income. The highest net economic income (11,876 RMB ha<sup>-1</sup>) of the harvest wheat considering both years was achieved under N application rate of 200 kg N ha<sup>-1</sup>. Likewise, compared with flood irrigation (10,209 RMB ha<sup>-1</sup>), drip irrigation and sprinkler irrigation significantly enhanced the mean net economic income by 10.5% and 13.4% during the two years, respectively.

**Table 2.** Results (F-values) of three-way ANOVAs for the effects of N rates (N), irrigation methods (Ir), year (Y), and their interactions on grain yield, biomass production, economic benefits, and water-use efficiency (WUE) over the two wheat-growing seasons in 2019 and 2020. Significance levels: \*  $p < 0.05$ , \*\*  $p < 0.01$ , \*\*\*  $p < 0.001$ , NS not significant.

| Source                 | df | Yield     | Shoot     | Root     | Total Biomass | Net Economic Income | Productivity Ratio (Output/Input) | WUE       |
|------------------------|----|-----------|-----------|----------|---------------|---------------------|-----------------------------------|-----------|
| Nitrogen (N)           | 3  | 26.59 *** | 24.69 *** | 4.46 **  | 27.82 ***     | 10.88 ***           | 106.42 ***                        | 26.44 *** |
| Irrigation method (Ir) | 2  | 12.50 *** | 8.04 ***  | NS       | 4.18 *        | 12.52 ***           | 9.86 ***                          | 12.47 *** |
| Year (Y)               | 1  | 24.14 *** | 55.69 *** | NS       | 49.32 ***     | 44.28 ***           | 7.77 **                           | 6.40 *    |
| N × Ir                 | 6  | 3.13 **   | NS        | 4.29 *** | NS            | 3.15 **             | 2.29 *                            | 3.12 **   |
| N × Y                  | 3  | NS        | 4.92 **   | NS       | 3.61 *        | NS                  | NS                                | NS        |
| Ir × Y                 | 2  | NS        | NS        | NS       | 3.36 *        | NS                  | NS                                | NS        |
| N × Ir × Y             | 6  | NS        | NS        | 2.58 *   | NS            | NS                  | NS                                | NS        |



**Figure 2.** Wheat grain yield (a) and plant biomass production (shoot biomass (b), root biomass (c), and total biomass (d)) response to N application rate during the two wheat-growing seasons in 2019 and 2020.



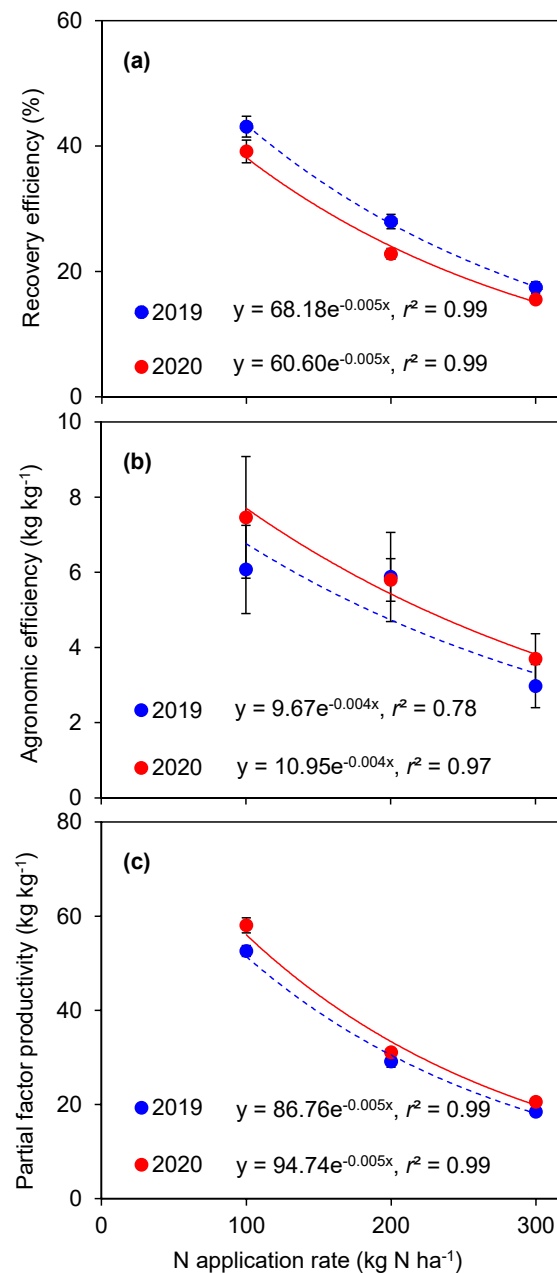
**Figure 3.** Wheat grain yield (kilograms of grain per hectare, kg ha<sup>-1</sup>; (a,b), net economic income in Chinese currency (RMB) per hectare (c,d), and ratio of output-to-input (O:I ratio; e,f) during the two wheat-growing seasons in 2019 and 2020. The different letters above the bar indicate significant differences ( $p < 0.05$ ) according to the Fisher's LSD test.

Generally, the ratio of output/input decreased with N application, while it was increased by water-efficient irrigation in both years (Figure 3e,f).

### 3.4. $RE_N$ , $AE_N$ , and $PFP_N$

The  $RE_N$ ,  $AE_N$ , and  $PFP_N$  values of wheat decreased sharply with the N application rate in both years, and they were significantly affected ( $p < 0.001$ ) by the N fertilizer, irrigation methods, year, and the interaction between N fertilizer and year (Figure 4, Table 3). N-L treatment (100 kg N ha<sup>-1</sup>) showed the highest  $RE_N$  (mean: 41.1%),  $AE_N$  (mean: 6.8 kg ka<sup>-1</sup>), and  $PFP_N$  (mean: 55.3 kg ka<sup>-1</sup>) between 2019 and 2020, which were 59.9%, 50.7%, and 64.7% higher than that of N-H treatment (300 kg N ha<sup>-1</sup>), respectively.

Generally,  $AE_N$  and  $PFP_N$  in 2020 were higher than in 2019, because of the higher grain yield in the second year. In contrast,  $RE_N$  in 2020 was lower than in 2019.



**Figure 4.** Recovery efficiency ( $RE_N$ , **a**), agronomic efficiency ( $AE_N$ , **b**) and partial factor productivity ( $PFP_N$ , **c**) as affected by N fertilization in the two wheat-growing seasons in 2019 and 2020.

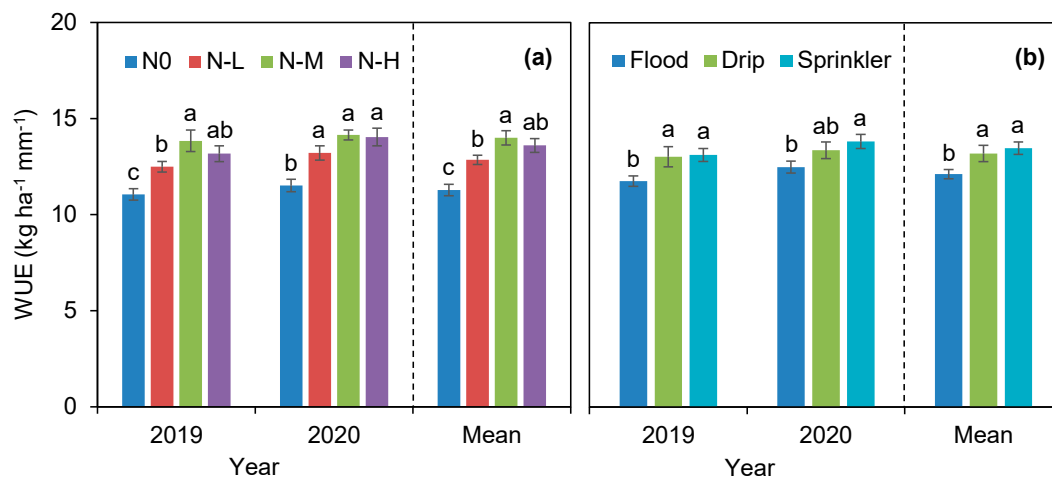
### 3.5. Water-Use Efficiency under Different Irrigation Methods

WUE was significantly influenced by the N application rate, irrigation method, year, and the interaction between N and irrigation during the two winter wheat seasons (Table 2). The N application significantly enhanced the WUE, and the highest WUE occurred with the N-M treatment (200 kg N ha<sup>-1</sup>) with medium N application, with the subsequent wheat grain yield. During the two winter wheat seasons, WUE under all the N fertilization treatments ranged from 12.5 to 13.8 kg ha<sup>-1</sup> mm<sup>-1</sup> and 13.2 to 14.1 kg ha<sup>-1</sup> mm<sup>-1</sup> in 2019 and 2020, respectively. Drip irrigation and sprinkler irrigation significantly enhanced WUE in both years, although there was no difference between the two water-efficient irrigation methods (Figure 5). Compared with flood irrigation (mean: 12.1 kg ha<sup>-1</sup> mm<sup>-1</sup>), drip

irrigation and sprinkler irrigation significantly enhanced the average WUE by 8.8% and 11.1% during the two winter wheat seasons, respectively.

**Table 3.** Three-way ANOVA for the effects of N rates, irrigation methods, year, and their interactions on nitrogen-use efficiencies ( $RE_N$ ,  $AE_N$ , and  $PPN$ ) over the two wheat-growing seasons in 2019 and 2020.

| Source                 | df | REN       |        |        | AEN    |       |        | PPN       |         |        |
|------------------------|----|-----------|--------|--------|--------|-------|--------|-----------|---------|--------|
|                        |    | SS        | F      | p      | SS     | F     | p      | SS        | F       | p      |
| Nitrogen (N)           | 2  | 9331.93   | 224.48 | <0.001 | 188.83 | 9.35  | <0.001 | 20,303.90 | 1005.54 | <0.001 |
| Irrigation method (Ir) | 2  | 104.62    | 2.52   | 0.088  | 270.17 | 13.38 | <0.001 | 270.77    | 13.41   | <0.001 |
| Year (Y)               | 1  | 304.70    | 14.66  | <0.001 | 10.31  | 1.02  | 0.316  | 223.90    | 22.18   | <0.001 |
| N × Ir                 | 4  | 78.25     | 0.94   | 0.445  | 229.82 | 5.69  | <0.001 | 228.85    | 5.67    | <0.001 |
| N × Y                  | 2  | 40.49     | 0.97   | 0.382  | 8.10   | 0.40  | 0.671  | 59.31     | 2.94    | 0.059  |
| Ir × Y                 | 2  | 90.09     | 2.17   | 0.122  | 34.19  | 1.69  | 0.191  | 34.24     | 1.70    | 0.191  |
| N × Ir × Y             | 4  | 107.24    | 1.29   | 0.282  | 106.64 | 2.64  | <0.05  | 106.29    | 2.63    | <0.05  |
| Model                  | 17 | 10,057.30 | 28.46  | <0.001 | 848.06 | 4.94  | <0.001 | 21,227.20 | 123.68  | <0.001 |
| Error                  | 72 | 1496.60   |        |        | 726.96 |       |        | 726.91    |         |        |



**Figure 5.** Water-use efficiency (WUE) as affected by N application (a) and irrigation methods (b) in the two wheat-growing seasons in 2019 and 2020. The different letters above the bar indicate significant differences ( $p < 0.05$ ) according to the Fisher's LSD test.

## 4. Discussion

### 4.1. Optimizing N Fertilization for Wheat Productivity and NUE

Winter wheat is an important cereal crop that is significantly influenced by the application of N fertilizer, especially in rain-fed regions such as the NCP. Farmers in this region always employ large amounts of N fertilizer for achieving higher crop yields, although crop productivity is not always increased with excessive N application, which causes unsustainable agricultural systems [4,6,14,17]. The results of this study show that wheat grain yield and biomass production have strong relationships with N application, which is in accordance with previous studies carried out in this region [16,22,23]. Grain yield and biomass production responded quadratically with N application rates in both years, and the highest grain yield occurred at 200 kg N ha<sup>-1</sup>. The agronomic optimum N application rate is 200 kg ha<sup>-1</sup>, which is similar to previous studies (168–252 kg N ha<sup>-1</sup>) conducted in this region [17,23], although it is much higher than the 96–168 kg N ha<sup>-1</sup> recommended by Wang et al. (2011) [16] and ≈30 kg N ha<sup>-1</sup> recommended by the USDA. The results described in this study show that the calculation of N application rates according to crop N demand helps reduce N application rates according to local farmer's practice while maintaining the winter wheat grain yield in the NCP.

The grain yield in this study was consistent with previous studies conducted in the same region, which have reported grain yields in a range from 3000 to 7000 kg ha<sup>-1</sup> [17,24].

The grain yield was slightly higher in 2020 than in 2019 (Table 2, Figure 3), which was likely due to the cumulative N effect whereby consecutive N applications enhanced soil N, and thus, yield, in the second year, as well as the higher air temperature in the 2020 growing season before the returning green stage (average air temperatures were 8.2 °C in 2020 and 7.6 °C in the 2019 growing seasons), resulting in more energy accumulated for wheat growth.

Realizing crop yield and NUE ‘win-win’ by optimizing N management is very important for sustainable agricultural production in the NCP. In the present study, a wide range of NUE (including REN, AEN, and PFPN) resulted from the different N application rates and showed a relatively low value. For example, the average AENs were 5.0 and 5.7 kg kg<sup>-1</sup> in 2019 and 2020, respectively. The results were similar to previous studies, where the agronomic NUEs were 6.4 kg kg<sup>-1</sup> and 5–10 kg kg<sup>-1</sup> in Zhejiang and Jiangsu province in southeast China, respectively [25] but lower than the mean AEN from 2000 to 2011 in China as assessed by Chuan et al. (2013) [26]. This was mainly due to the low AEN in the high N application rate. Dobermann (2007) [27] reported that the AEN for cereals ranged between 10 and 30 kg kg<sup>-1</sup> in developing countries, indicating that the AEN could reach over 25 kg kg<sup>-1</sup> in a well-managed system with low N input. Generally, NUE was expressed as fairly low in this study, highlighting the need to improve N management practices, such as split applications with base fertilization and top dressing in the reviving stage of winter wheat [17]. In the present study, there is only one N application without top dressing. It is possible to improve wheat yield and NUE simultaneously with an appropriate reduction in N.

#### 4.2. Water-Efficient Irrigation Improved Wheat Yield and WUE

Shortages of irrigation water resources present more challenges due to the long-term cultivation of high-water-consumptive crops and non-sustainable irrigation methods (e.g., flood irrigation) in the NCP [9,28]. Water-efficient irrigation methods (e.g., drip irrigation and sprinkler irrigation) are necessary for adapting to water scarcity, and they are also beneficial for wheat production and water conservation strategies. It is widely believed that an increase in the agricultural WUE is vital for maintaining crop yields while mitigating water shortages [8–10,21,29], despite the fact that flood irrigation is a widely used management despite the WUE being low in the NCP [8,11]. In the present study, drip irrigation and sprinkler irrigation significantly increased wheat yield, and thus, the WUE, in both years, which was mainly due to the two more efficient irrigation methods providing more viable water for wheat absorption and utilization. Drip irrigation could efficiently limit deep water percolation and reduce water evaporation in the soil, thus enhancing the WUE [30,31]. Low WUE in cereal production is a common problem for sustainable agriculture throughout the world, especially in serious water shortage areas [32]. This study showed that employing water-efficient irrigation methods (e.g., drip irrigation and sprinkler irrigation) can effectively enhance wheat grain yield and WUE in the NCP. This result has an important implication for wheat production and water efficiency in rain-fed areas with serious water shortages, because the irrigated wheat area is approximately seven million hectares in the NCP [9].

#### 4.3. Economic Performance

Yield production has a direct impact on the economic performance of wheat. N fertilization and irrigation are two vital factors influencing wheat production, and thus, the economic performance. Excessive N application and large amounts of irrigation with low WUE (e.g., flood irrigation) will incur extra costs. In the present study, the net economic income showed a quadratic relationship with N, and the highest occurred with N-M treatment (200 kg N ha<sup>-1</sup>); however, when considering the ratio of output/input, there was lower N application with a higher ratio of output/input because of the extra expense such as the N fertilizer and pesticide. Similarly, drip irrigation and sprinkler irrigation exhibited a higher grain yield and net economic income relative to flood irrigation. Although the

ratio of output/input showed no difference among the three irrigation methods, drip irrigation and sprinkler irrigation were expressed higher than flood irrigation. Therefore, comprehensively considering the wheat productivity and economic performance, water-efficient irrigation accompanied with N application rates of 200 kg ha<sup>-1</sup> is optimal for achieving high economic returns for local farmers in the NCP.

## 5. Conclusions

The results of this study show that wheat grain yield and biomass production are strongly dependent on N fertilization, exhibiting a quadratic relationship. The highest grain yield occurred with the 200 kg N ha<sup>-1</sup> application rate in the two years studied. Drip irrigation and sprinkler irrigation significantly enhanced the wheat grain yield but not biomass production. The highest net economic income was exhibited at a 200 kg ha<sup>-1</sup> N application rate accompanied with water-efficient drip irrigation and sprinkler irrigation, indicating that the economic optimum N rate could be properly reduced for high grain yield and economic performance for local farmers. AEN, REN, and PFPN were relatively low and showed strongly negative relationships with the N fertilizer application rate in both years. The two water-efficient irrigation methods (drip irrigation and sprinkler irrigation) significantly enhanced the WUE. This study suggests that highly water-efficient efficient irrigation methods accompanied with N application rates of 200 kg ha<sup>-1</sup> are beneficial for achieving better economic performance for local farmers in the NCP.

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