The Coupled Effects of Irrigation Scheduling and Nitrogen Fertilization Mode on Growth, Yield and Water Use Efficiency in Drip-Irrigated Winter Wheat

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Abstract: Sound irrigation and nitrogen management strategies are necessary to achieve sustainable yield and water use efficiency of winter wheat in the North China Plain (NCP). The coupled effects of irrigation scheduling and the nitrogen application mode (NAM) on winter wheat growth, yield and water use efficiency under drip irrigation were evaluated with a two-year field experiment, which consisted of three irrigation scheduling levels (ISLs) (irrigating when soil water consumption (SWC) reached 20, 35 and 50 mm, referred as I20, I35 and I50, respectively) and three nitrogen application modes (NAMs) (ratio of basal application and topdressing as 50:50, 25:75 and 0:100, referred as N50:50, N25:75 and N0:100, respectively). The experimental results showed that irrigating winter wheat at ISL135 substantially (p < 0.05) improved the grain yield by 15.89%, 3.32% and 14.82%, 4.31% compared with those at ISL I20 and I50 in 2017–2018 and 2018–2019 growing seasons, respectively. NAM N25:75 appeared very beneficial in terms of grain yield, yield components and WUE as compared to other NAM levels. The maximum grain yield (8.62 and 9.40 t ha−1) and water use efficiency (1.88 and 2.09 kg m−3) were achieved in treatment I35N25:75 in two growing seasons over those in other treatments. The results in this study may deliver a scientific basis for irrigation and nitrogen fertilization management of the drip-irrigated winter wheat production in the NCP.

Keywords: winter wheat; drip irrigation; irrigation scheduling level; nitrogen application mode; grain yield; water use efficiency

1. Introduction

The dramatically increasing population is putting a notable strain on natural resources in China. In the past decades, nearly all efforts were focused on the development of the potential of natural resources for increasing crop yield to meet the food demand of the great population, which resulted in overutilization of resources, decreased total factor productivity, and environmental degradation. In recent years, the main focus has been shifted to sustainable production technologies with efficient utilization of resources [1]. Among the various resources, irrigation water and fertilizers are two key inputs having maximum contribution to crop productivity. While, among food crops, China is the largest wheat production countries of the world; during 2017 the world wheat production was 761.3 million tons with 134.3 million tons production in only China [2]. The North China Plain (NCP) is the largest and most important wheat growing area, with almost two-thirds of China’s wheat production and is very important to food security for China.
The NCP is the scarcest water region in China [3] as it possesses less than 5% of the country’s water resources [4]. Immoderate usage of ground water for irrigation results in the quick decline of the groundwater table, specifically in the northern part of the NCP, leading to hydrological imbalance and unmaintained agricultural productivity [5,6]. Water tables decreased approximately up to 1 m every year, mainly because of water withdrawals for irrigation of winter wheat [7]. Moreover, the production of winter wheat in NCP is distinguished by low water use efficiency (WUE). The irrigation practices in NCP were optimized to two times from 3–5 times, which resulted in improved WUE [8,9]. However, these results are based on the experiment under traditional flood irrigation method. High-performance irrigation methods like drip irrigation systems are generally recommended to overcome this issue as they dramatically enhance the water use efficiency more than outmoded irrigation methods [10,11].

Drip irrigation is one of the most important water-saving irrigation systems with high water and fertilizer use efficiency [12,13]. To date, drip irrigation has been well adopted in low-density and large-sized crops like cotton as reported by [14,15], corn [16], cash crops [17] and in fruit production [18]. However, this irrigation system, having very high water and fertilizer use efficiency, is seldom applied to small-sized and high-density crops like wheat [19].

Fertilizer application is also one of the vital inputs, making a considerable contribution to improving nutritional quality and yield. But unfortunately, excessive nitrogen (N) is being applied and more than 50% is lost to the environment, which eventually causes environmental pollution [20,21]. Topdressing of N fertilizer at the tillering and heading stage is vital to regulate the canopy and to enhance biomass [22]. On the other hand, the supply of N to crops is determined by plant-available N contents in the soil at growing time. Furthermore, the movement of nutritional elements generally relies on soil water content status [23]. The fluctuation in nitrate concentration around the roots can influence root hydraulic properties, which may lead to more extraction of soil water from a nitrate-rich piece of soil [24]. Thus, soil water and nitrate often show a coupling effect on the crop yield [25].

The coupling effects of irrigation and the nitrogen application mode (NAM), especially in winter wheat, are still not distinct. Thus, the study intends to explore the scarce information about the effects of different irrigation scheduling levels with different ratios of basal to topdressing N fertilizer on vegetative growth, grain yield, yield components, water consumption and water use efficiency (WUE) of winter wheat, and to determine the reasonable combination of irrigation scheduling and nitrogen application mode levels for winter wheat production in NCP. The results will provide insight into how irrigation and N fertilizer management can be manipulated for the better performance of drip-irrigated winter wheat.

2. Materials and Methods

2.1. Experimental Site and Weather Description

The two-year field experiment was conducted during the consecutive winter wheat growing seasons (2017–2018 and 2018–2019) at the Qiliying Experimental Station (35°08' N, 113°45' E, 81 m altitude) of the Farmland Irrigation Research Institute of the Chinese Academy of Agricultural Science (CAAS), located at Xinxiang, Henan Province (Figure 1). The dominant soil specifications of the experimental fields are presented in Table 1. The soil was sandy loam with average available soil nitrogen (40.20 mg kg\(^{-1}\)), phosphorous (11.90 mg kg\(^{-1}\)) and potassium content of 100.51 mg kg\(^{-1}\). The soil organic matter, pH and electric conductivity were 1.10%, 8.5 and 257.6 μS cm\(^{-1}\), respectively.
Figure 1. Location of experimental station in the North China Plain (NCP). (Source, [26]).

### Table 1. Soil specifications of experimental field. (Source, [26]).

| Layer (cm) | Bulk Density (g cm\(^{-3}\)) | Particle Size (%) | Soil Texture | \(\theta_f\) (cm\(^3\) cm\(^{-3}\)) | \(\theta_r\) (cm\(^3\) cm\(^{-3}\)) |
|------------|-------------------------------|-------------------|--------------|-----------------|-----------------|
| 0–20       | 1.56                          | 53.06             | 43.14        | 3.80            | Sandy Loam      | 0.341           | 0.163           |
| 20–40      | 1.58                          | 47.96             | 45.43        | 6.61            | Loam            | 0.308           | 0.157           |
| 40–60      | 1.54                          | 45.61             | 48.33        | 6.06            | Sandy Loam      | 0.327           | 0.181           |
| 60–80      | 1.42                          | 47.96             | 47.49        | 4.55            | Sandy Loam      | 0.283           | 0.181           |
| 80–100     | 1.45                          | 81.48             | 16.95        | 1.57            | Loamy Sand      | 0.294           | 0.173           |
| Average    | 1.51                          | 55.21             | 40.27        | 4.52            | Sandy Loam      | 0.311           | 0.171           |

Note: \(\theta_f\) is field capacity and \(\theta_r\) residual water content.

The daily weather data like atmospheric temperature (maximum and minimum), wind speed, sunshine hours, precipitation and relative humidity were collected from an automatic weather station installed in the experimental station. Based on the previous climatic data, the total precipitation varied from 60 to 200 mm during winter wheat growing season (mid-October to early June) with seasonal air temperatures of 10 to 12 °C. The approximate seasonal water consumption for winter wheat was 450–500 mm [27]. The average temperature was 9.81 and 9.30 °C, and total precipitation 238 mm and 117 mm during the wheat growing seasons in 2017–2018 and 2018–2019, respectively.

2.2. Experimental Design and Field Implementation

This experiment followed a split plot design with irrigation scheduling as the main plot and nitrogen application mode as sub-plot. There was a total of nine treatments, and each treatment had three replications with a sub-plot size of 3 m wide by 20 m long. There were three irrigation scheduling levels on the base of soil water consumption (SWC). Irrigation (with quotas of 20 mm, 35 mm and 50 mm) was carried out whenever SWC reached 20 mm (I20), 35 mm (I35) and 50 mm (I50), respectively. In treatments related to the nitrogen application mode, three levels of NAM were arranged and referred to as N50:50 (50% as basal and 50% as topdressing), N25:75 (25% as basal and remaining 75% as topdressing) and N0:100 (all nitrogen as topdressing). The basal dose was applied before sowing (Julian day 287 in both seasons) while the topdressing was done with fertigation at returning green (Julian day 71 in both seasons), jointing (Julian day 98 and 93 in 2018 and 2019, respectively) and at grain filling stage (Julian day 133 and 136 in 2018 and 2019, respectively). During the 2017–2018 growing season, 10 mm irrigation was carried out in several cases to apply fertilizer even if no irrigation was required and this irrigation
amount was deducted from the designated amount for the next irrigation (i.e., Julian day 98 and 133 of the 2017–2018 growing season for I35 and I50 in Table 2) [28].

Table 2. Irrigation scheduling for all treatments during 2017–2018 and 2018–2019 wheat seasons.

| Treatment | 2017–2018 |  | 2018–2019 |  |
|-----------|-----------|---|-----------|---|
| Date (Amount) (Julian Day, mm) | Total Amount (mm) | Date (Amount) (Julian Day, mm) | Total Amount (mm) |
| I20       | 71 (20), 98 (20), 133 (20) | 60 | 71 (20), 93 (20), 115 (20), 129 (20), 136 (20) | 100 |
| I35       | 71 (35), 98 (10), 123 (25) **, 133 (10) * | 80 | 71 (35), 93 (35), 115 (35), 136 (35) | 140 |
| I50       | 71 (50), 98 (10), 126 (40) **, 133 (10) * | 110 | 71 (50), 93 (50), 123 (50), 136 (50) | 200 |

Note: * During the 2017–2018 growing season, 10 mm water was irrigated for applying fertilizer even if no irrigation was required; ** Indicates that a 10-mm irrigation amount was deducted from the designated irrigation treatment for next irrigation scheduling (i.e., Julian day 123 and 126 of 2017–2018 growing season for I35 and I50). * Represents the time of nitrogen application.

Seedbeds were prepared by plowing to a 20-cm depth with a tractor-drawn rotary cultivator, and larger soil clods were smoothed by using a harrow to ensure a completely flat bed. The high-yielding winter wheat (Triticum aestivum L.) cultivar “Zhoumai 22” was sown on 15 October 2017 and 2018 at 180 kg ha$^{-1}$ with 20 cm row spacing. A total of 270 kg ha$^{-1}$ of urea was applied according to the experimental design described above in both growing seasons. The total amount of 105 kg ha$^{-1}$ of calcium superphosphate and 120 kg ha$^{-1}$ of potassium sulfate were applied as basal fertilizer in all treatments. The experimental plots were harvested on 31 May 2018 and 3 June 2019.

The drip irrigation lateral spacing was 60 cm, while the discharge rate of the dripper was 2.2 L h$^{-1}$ under a working pressure of 0.10–0.15 MPa. The flow meters were installed in each sub-plot to monitor the exact amount of irrigation water application. Farmers in NCP usually irrigate winter wheat in early spring at returning green stage depending on soil moisture status [29]. Considering this typical schedule, the first irrigation for all treatments was conducted on the same date after the wheat turned green, and subsequent irrigations were determined on the basis of SWC according to the experimental design described above. The amount and date of each irrigation and nitrogen fertilizer application in both wheat growing seasons are presented in Table 2.

2.3. Measurement of Crop Evapotranspiration (ETc) and Water Use Efficiency (WUE)

To assess the ETc, soil samples were excavated after five days of each irrigation for 0–10, 10–20, 20–30, 30–40, 40–60, 60–80 and 80–100 cm soil layers in each sub-plot by auger, and then dried and weighed to measure moisture contents.

Crop evapotranspiration was calculated by the soil water balance method [30]:

\[
ETc = I + P + U - (R + D) \pm \Delta S
\]  

where ETc is the crop evapotranspiration during a time period, P is precipitation (mm); I is applied irrigation amount (mm); \(\Delta S\) is change in the soil water storage, U is upward capillary rise, while R and D are surface runoff (mm) and downward drainage, respectively. It should be noted that all other parameter values are for the same time period as determining ETc. Here, the upward capillary rise, surface runoff and downward drainage were not investigated during two growing seasons and considered as zero. Deep groundwater table, no intense rainfall and irrigation events during the two experimental periods and surrounding all the experimental plots with high ridges were the main reasons.

Soil water consumption (SWC) was calculated by the equation as given below:

\[
SWC = \text{Soil moisture after irrigation} - \text{Soil moisture before irrigation.}
\]
Water use efficiency (kg m\(^{-3}\)) is an indicator of effective irrigation water utilization for increasing crop production. WUE of grain yield (Y, kg m\(^{-2}\)) was determined according to [31]:

\[
\text{WUE} = \frac{Y}{ETc}. \quad (3)
\]

2.4. Growth and Yield Related Parameters

Leaf area index (LAI) and plant height of winter wheat were recorded at 10- to 15-day intervals from 10 randomly collected plant samples for each sub-plot. LAI was determined according to [32]. According to this method, leaf length and leaf width of each leaf from 10 plants were measured with a ruler, and leaf area per plant (LA) was calculated by the following formula and presented in m\(^2\):

\[
L_A = \frac{\sum_{i=1}^{n} A_i}{n} = \frac{\sum_{i=1}^{n} [\sum_{j=1}^{m} (L_j \times W_j) \times 0.8]}{n}. \quad (4)
\]

LAI was set as the ratio of total leaf area to land area over the experimental plot.

\[
LAI = \frac{L_A \times N}{S} \quad (5)
\]

where, \(n\) is the number of plant samples used to determine leaf area, \(n = 10\); \(A_i\) is the leaf area of \(i\)th plant; \(m\) is the number of leaf in \(i\)th plant, while \(L_j\) and \(W_j\) are length and width of the \(j\)th leaf in \(i\)th plant (both measured in cm); \(N\) is the number of plants (including tillers) in 1 m of row, and \(S (S = 0.2 \text{ m})\) is row spacing.

Plant height was measured with 10 plants and presented as mean of the heights from ground surface to top of canopy during early growth stages and from ground surface to top of spikelet (excluding awns) after earring stage. At harvest, 10 plants were selected in each sub-plot to determine plant height, yield components like number of grains per spike and spike length. Finally, 1 m\(^2\) area of plants was sampled to quantify number of spikes per unit area, grain yield (t ha\(^{-1}\)), aboveground biomass (t ha\(^{-1}\)) and 1000-grain weight (g) for every experimental sub-plot. The grain yield of each experimental sub-plot was measured by weighting grains after naturally drying to 12% moisture content. The harvest index (HI) was determined by the equation given below:

\[
\text{HI} = \frac{\text{Grain yield (t ha}^{-1})}{\text{Aboveground biomass (t ha}^{-1}). \quad (6)
\]

2.5. Statistical Analysis

All collected experimental data were statistically analyzed by using Statistix 8.1 software under split plot design with three replications. Analysis of variance (ANOVA) was done to evaluate mean and interaction terms of irrigation scheduling and nitrogen application mode treatments. Furthermore, means of the different treatments were compared by least significant difference (LSD) at 5%, 1% and 0.1% probability level.

3. Results

3.1. Effects of Different Irrigation Scheduling Levels (ISLs) and NAM Treatments on Crop Growth

Temporal variations in LAI and plant height of winter wheat under different irrigation and nitrogen treatments are plotted in Figures 2–5. Generally, the LAI and plant height showed a very similar temporal change trend under all ISLs and NAMs and during two growing seasons. Under all NAM levels, the ISL of SWC = 50 mm (I50) always exhibited the greatest LAI and plant height values, followed by those in I35 and I20 treatments during both growing seasons (Figures 2 and 4). However, the greatest LAI and plant height was observed under N50:50 treatment, followed by those in N25:75 and N0:100 at early stages (returning green and jointing), but the LAI trended as N0:100 > N25:75 > N50:50 at late stages (booting, earring and harvesting) (Figures 3 and 5), which illustrated that more N application was beneficial to LAI and plant height, no matter in early or late stages.
Figure 2. Temporal changes in leaf area index of winter wheat across irrigation scheduling levels (ISLs) in (a) N50:50; (b) N25:75; (c) N0:100 during 2017–2018 and in (d) N50:50; (e) N25:75; (f) N0:100 during 2018–2019 growing season.

Figure 3. Temporal changes in leaf area index of winter wheat across nitrogen application modes (NAMs) in (a) I20; (b) I35; (c) I50 during 2017–2018 and in (d) I20; (e) I35; (f) I50 during 2018–2019 growing season.
Peak values of LAI were noticed at booting stage in all treatments and then tended to decrease till harvesting in both seasons. Maximum LAI and plant height during both study seasons was attained at treatment I50N0:100, while the minimum values were at I20N50:50.
3.2. Effects on Yield and Its Components

The data regarding grain yield of each treatment are presented in Table 3. Upon perusal of data, it was found that irrigation scheduling and nitrogen application modes had very significant effects (p < 0.001) on grain yield during both growing seasons, while their interactive effects were significant at p < 0.01 and p < 0.05 during the 2017–2018 and 2018–2019 growing seasons, respectively. Grain yield varied from 6.99 t ha\(^{-1}\) to 8.62 t ha\(^{-1}\) and 7.55 t ha\(^{-1}\) to 8.95 t ha\(^{-1}\), while the maximum grain yield 8.62 t ha\(^{-1}\) and 9.40 t ha\(^{-1}\) was attained under I35N25:75 and the minimum yield 6.99 t ha\(^{-1}\) and 7.55 t ha\(^{-1}\) in I20N50:50 in the 2017–2018 and 2018–2019 growing seasons, respectively.

### Table 3. Statistical analysis results of winter wheat grain yield (t ha\(^{-1}\)) during the 2017–2018 and 2018–2019 growing seasons.

| Season       | 2017–2018          | 2018–2019          |
|--------------|---------------------|---------------------|
| Treatment    | N50:50 | N25:75 | N0:100 | Average | N50:50 | N25:75 | N0:100 | Average |
| I20          | 6.99   | 7.50   | 7.29   | 7.26\(^{c}\) | 7.55 | 8.13   | 7.93   | 7.87\(^{c}\) |
| I35          | 8.22   | 8.62   | 8.40   | 8.41\(^{a}\) | 8.76 | 9.40   | 8.95   | 9.04\(^{a}\) |
| I50          | 7.99   | 8.30   | 8.14   | 8.14\(^{a}\) | 8.36 | 8.99   | 8.64   | 8.66\(^{b}\) |
| Average      | 7.73\(^{c}\) | 8.14\(^{a}\) | 7.94\(^{b}\) | 7.94 | 8.22\(^{c}\) | 8.84\(^{a}\) | 8.51\(^{b}\) | 8.52 |

Statistics: I: *** I: *** I: *** I: *** I: *** I: *** I: *** I: ***
Analysis: N: *** N: *** N: ***
Results: I \(\times\) N: * I \(\times\) N: *

Average values indicating different letters are significantly different at p < 0.05. Significance level: * (p < 0.05), ** (p < 0.01), *** (p < 0.001).

Among the three NAMs, average grain yield on the medium ISL (I35) was the highest, and decreased on maximum (I50) and minimum (I20) ISL during both study years. The average grain yields based on different ISLs indicated that grain yield was significantly improved by increasing the percentage of top-dressed nitrogen from 50% to 75% and then decreasing all the nitrogen as topdressing.

The data in Table 4 show that all yield components varied significantly at p < 0.001 under various ISLs and NAMs during both growing seasons, but their interactive effects varied at 0.05 in the 2017–2018 season, and at 0.001 significance level besides spikes per unit area (SPUA) at 0.05 level in the 2017–2018 season. Generally, yield components gave better results with increasing the ISL from I20 to I35 but showed a negative trend with continually increasing the ISL to I50.

### Table 4. Coupling effect of irrigation scheduling and nitrogen application modes on yield components of winter wheat during the 2017–2018 and 2018–2019 growing seasons.

| Season       | 2017–2018          | 2018–2019          |
|--------------|---------------------|---------------------|
| Treatment    | SL (cm) | GS | SPUA (10\(^{4}\) ha\(^{-1}\)) | TGW (g) | SL (cm) | GS | SPUA (10\(^{4}\) ha\(^{-1}\)) | TGW (g) |
| I20N50:50:00 | 7.24\(^{e}\) | 26.70\(^{f}\) | 422.67\(^{e}\) | 44.42\(^{e}\) | 7.79\(^{e}\) | 30.40\(^{f}\) | 500\(^{f}\) | 49.05\(^{i}\) |
| I20N50:75:20 | 8.17\(^{abcd}\) | 30.40\(^{d}\) | 473\(^{cd}\) | 50.11\(^{bc}\) | 8.69\(^{bc}\) | 35.60\(^{d}\) | 566.67\(^{def}\) | 50.90\(^{e}\) |
| I20N10:00:25 | 7.94\(^{cd}\) | 28.20\(^{e}\) | 463.35\(^{d}\) | 48.41\(^{d}\) | 8.39\(^{d}\) | 34.30\(^{e}\) | 540\(^{ef}\) | 50.14\(^{d}\) |
| I35N0:100:25 | 8.20\(^{abc}\) | 31.40\(^{cd}\) | 474.33\(^{cd}\) | 49.68\(^{cd}\) | 8.68\(^{bc}\) | 35.70\(^{d}\) | 603.33\(^{cde}\) | 50.59\(^{f}\) |
| I35N50:25:50 | 8.47\(^{a}\) | 37.60\(^{a}\) | 549\(^{a}\) | 51.97\(^{a}\) | 8.83\(^{ab}\) | 43.90\(^{a}\) | 681.67\(^{a}\) | 52.86\(^{a}\) |
| I35N10:00:50 | 8.32\(^{ab}\) | 34.70\(^{b}\) | 499\(^{bc}\) | 51.51\(^{a}\) | 8.94\(^{a}\) | 38.10\(^{b}\) | 655\(^{abc}\) | 52.02\(^{c}\) |
| I50N0:100:50 | 7.88\(^{d}\) | 28.70\(^{e}\) | 487.33\(^{bcd}\) | 48.59\(^{d}\) | 8.40\(^{d}\) | 32.60\(^{f}\) | 611.67\(^{bcd}\) | 49.83\(^{h}\) |
| I50N25:50:75 | 8.27\(^{ab}\) | 32.10\(^{c}\) | 511.33\(^{bcd}\) | 51.74\(^{a}\) | 8.69\(^{bc}\) | 36.60\(^{c}\) | 671.67\(^{ab}\) | 52.30\(^{b}\) |
| I50N10:100:25 | 8.11\(^{bcd}\) | 30.60\(^{d}\) | 491.33\(^{bc}\) | 51.10\(^{ab}\) | 8.61\(^{c}\) | 35.30\(^{d}\) | 620\(^{abcd}\) | 51.68\(^{d}\) |

I: *** I: *** I: *** I: *** I: *** I: *** I: *** I: ***
N: *** I: *** I: *** I: *** I: *** I: *** I: *** I: ***
I \(\times\) N: * I \(\times\) N: *

Note: SL is spike length, GS is number of grains per spike, SPUA represents number of spikes per unit area, TGW is 1000-grain weight, I = Irrigation scheduling, N = Nitrogen basal topdressing ratios. Mean values (n = 3) indicating different letters are significantly different at p < 0.05. NS stands for non-significant at p < 0.05 level. Significance level: * (p < 0.05), ** (p < 0.01), *** (p < 0.001).
As an average of NAMs, ISL I20 reduced the spike length, 1000-grain weight, grain per spike and spikes per unit area by 6.56%, 6.67%, 17.75%, and 10.73%, respectively, during the 2017–2018 growing season as compared to ISL I35, whose corresponding values were 5.95%, 3.46%, 14.78%, and 17.18% during the 2018–2019 season, respectively.

Notably, across all NAMs, it was found that increasing the percentage of top-dressed nitrogen from 50% to 75% significantly improved yield components, but applying all nitrogen fertilizer as topdressing, such as in the N0:100 treatment, lowered the yield components more than N25:75. Averaging across the ISLs, the NAM N50:50, compared to N25:75, caused reductions of 6.38%, 7.23%, 13.29%, and 9.72% in the 2017–2018 growing season, and 5.10%, 4.22%, 14.99%, 10.68% reductions in the 2018–2019 growing season, in spike length, 1000-grain weight, grain per spike and spikes per unit area, respectively.

3.3. Effects on Aboveground Biomass and Harvest Index

Data given in Table 5 indicate that ISL and NAM both affected significantly ($p < 0.001$) the aboveground biomass during both study years. Increasing the ISL and topdressing percentage positively increased the aboveground biomass. Across all the NAM levels, I50 treatment increased the biomass by 25.34%, 24.78%, and 11.29%, 11.10% more than the I20 and I35 treatments during both seasons, respectively. Furthermore, averaging aboveground biomass values across three ISL treatments, N0:100 increased the biomass by 18.77%, 18.06%, and 7.78%, 7.69% more than those from N50:50 and N25:75 in both seasons, respectively. Statistically, a higher irrigation quota (I50) with higher topdressing percentage (N0:100) attained the maximum biomass (18.03 and 18.27 t ha$^{-1}$) during the 2018 and 2019 seasons, respectively. Additionally, the lowest biomass (12.58 and 12.87 t ha$^{-1}$) resulted from the combination of lower irrigation quota (I20) and topdressing percentage (N50:50) in both seasons.

Table 5. Statistical analysis results of aboveground biomass (AB) (t ha$^{-1}$) of winter wheat during the 2017–2018 and 2018–2019 growing seasons.

| Treatment | 2017–2018 | 2018–2019 |
|-----------|-----------|-----------|
| I20       | 12.58     | 13.17     | 14.91 | 13.55$^c$ | 12.87 | 13.4 | 15.13 | 13.80$^c$ |
| I35       | 13.53     | 15.59     | 16.67 | 15.26$^b$ | 13.8 | 15.82 | 16.88 | 15.50$^b$ |
| I50       | 15.66     | 17.27     | 18.03 | 16.99$^a$ | 15.92 | 17.47 | 18.27 | 17.22$^a$ |
| Average   | 13.92$^c$ | 15.34$^b$ | 16.54$^a$ | 15.27 | 14.20 | 15.56 | 16.76 | 15.51 |

Statistics: $I$ = Irrigation scheduling, $N$ = Nitrogen application mode. Average values indicating different letters are significantly different at $p < 0.05$. Significance level: $^*$ ($p < 0.05$), $^{**}$ ($p < 0.01$), $^{***}$ ($p < 0.001$).

The harvest index (HI) was markedly affected by ISL and NAM (Table 6). HI varied from highest at 0.61 in treatment I35N50:50 to lowest at 0.45 in I50N0:100 during the 2017–2018 growing season, and from highest at 0.63 in I35N50:50 to lowest at 0.52 in I50N0:100 and other two treatments in the 2018–2019 season. Generally, the HI values in the 2018–2019 season were slightly higher than those in the 2017–2018 season.

Comparing the average values of HI cross different ISLs and NAM levels, it may be concluded that HI did not vary strictly following a specific mode but may be described generally as: HI decreased with an increasing percentage of top-dressed nitrogen, but the range appearing from N50:50 to N25:75 was significantly smaller than that from N25:75 to N0:100. While the ISL varied from 20 mm to 35 mm, the HI had a slight increase, but decreased remarkably while the ISL increased continually from 35 mm to 50 mm.
Table 6. Statistical analysis results of the harvest index (HI) of winter wheat during the 2017–2018 and 2018–2019 growing seasons.

| Season          | 2017–2018 | 2018–2019 |       |       |       | Average |       |       |       |       |       |       |
|-----------------|-----------|-----------|-------|-------|-------|---------|-------|-------|-------|-------|-------|-------|
| Treatment       | N50:50    | N25:75    | N0:100| Average|       | N50:50  | N25:75| N0:100| Average|       |       |       |
| I20             | 0.55      | 0.57      | 0.49  | 0.54 b| 0.59  | 0.61    | 0.52  | 0.57 a|        |       |       |       |
| I35             | 0.61      | 0.55      | 0.50  | 0.55 a| 0.63  | 0.60    | 0.53  | 0.59 a|        |       |       |       |
| I50             | 0.51      | 0.48      | 0.45  | 0.48 c| 0.53  | 0.52    | 0.52  | 0.52 b|        |       |       |       |
| Average         | 0.56 a    | 0.53 b    | 0.48 c| 0.52  | 0.58 a| 0.58 b  | 0.52  | 0.56  |        |       |       |       |

Statistics Analysis Results

I *** I *
N *** N ***
I × N *** I × N ***

Average values indicating different letters are significantly different at p < 0.05. Significance level: * (p < 0.05), ** (p < 0.01), *** (p < 0.001).

3.4. Effects on Crop Evapotranspiration (ETc) and Water Use Efficiency (WUE)

In both growing seasons, a significant difference (p < 0.001) in ETc was found for different irrigation and nitrogen management strategies (Table 7). The mean ETc values for I20, I35 and I50 treatments were 423.15, 463.09 and 520.53 mm in the 2017–2018 season, and 413.46, 452.32 and 485.85 mm in the 2018–2019 season, respectively, which indicated that ETc increased significantly with increasing irrigation quota. However, the data presented in Table 7 showed only a slight trend that ETc increased with the rising percentage of top-dressed nitrogen.

Table 7. Statistical analysis results of crop evapotranspiration (ETc) (mm) of winter wheat during the 2017–2018 and 2018–2019 growing seasons.

| Season          | 2017–2018 | 2018–2019 |       |       |       | Average |       |       |       |       |       |       |
|-----------------|-----------|-----------|-------|-------|-------|---------|-------|-------|-------|-------|-------|-------|
| Treatment       | N50:50    | N25:75    | N0:100| Average|       | N50:50  | N25:75| N0:100| Average|       |       |       |
| I20             | 421.1     | 422.1     | 426.2 | 423.1 c| 402.5 | 415.0   | 422.8 | 413.5 c|        |       |       |       |
| I35             | 460.5     | 457.6     | 471.2 | 463.1 b| 445.2 | 450.1   | 461.6 | 452.3 b|        |       |       |       |
| I50             | 511.8     | 518.8     | 531.0 | 520.5 a| 475.0 | 485.6   | 497.0 | 485.8 a|        |       |       |       |
| Average         | 464.4 b   | 466.2 b   | 476.1 a| 468.9 | 440.9 c| 450.2 b | 460.5 a| 450.5  |        |       |       |       |

Statistics Analysis Results

I *** I ***
N *** N ***
I × N *** I × N ***

Average values indicating different letters are significantly different at p < 0.05. Significance level: * (p < 0.05), ** (p < 0.01), *** (p < 0.001).

The variance analysis of WUE data showed that irrigation scheduling and nitrogen fertilization modes significantly (p < 0.001) influenced the WUE during both study seasons (Table 8). It was observed that WUE increased with an increase in ISL and NAM up to a certain limit and then tended to decrease. A rise in WUE was noticed when the ISL was changed from I20 to I35 and NAM from N50:50 to N25:75. Interestingly, WUE declined dramatically when ISL changed from I35 to I50 and NAM from N25:75 to N0:100 during both study seasons. Compared to I20 and I50, I35 significantly increased WUE by 5.23% and 16.03% in the 2017–2018 season, and by 5.26% and 12.36% in the 2018–2019 season. Otherwise, compared to the greatest WUE in NAM N25:75, the WUE in N50:50 and N0:100 both decreased by 4.57% in the 2017–2018 season, and by 5.08% and 6.09%, respectively, in the 2018–2019 season.
Table 8. Statistical analysis results of water use efficiency (WUE) (kg m\(^{-3}\)) of winter wheat during the 2017–2018 and 2018–2019 growing seasons.

| Season  | 2017–2018 | 2018–2019 |  | Average | N50:50 | N25:75 | N0:100 | Average | N50:50 | N25:75 | N0:100 | Average |
|---------|-----------|-----------|---|---------|--------|--------|--------|---------|--------|--------|--------|---------|
| I20     | 1.66      | 1.78      | 1.71 | 1.72 \(^b\) | 1.88   | 1.96   | 1.87   | 1.90 \(^b\) |        |        |        |         |
| I35     | 1.78      | 1.88      | 1.78 | 1.81 \(^a\) | 1.97   | 2.09   | 1.94   | 2.00 \(^a\) |        |        |        |         |
| I50     | 1.56      | 1.60      | 1.53 | 1.56 \(^c\) | 1.76   | 1.85   | 1.74   | 1.78 \(^c\) |        |        |        |         |
| Average | 1.67 \(^b\) | 1.75 \(^a\) | 1.67 \(^b\) | 1.70   | 1.87 \(^b\) | 1.97 \(^a\) | 1.85 \(^b\) | 1.90 |        |        |        |         |

Statistics Analysis Results

I *** I **
N *** N ***
I \(^\times\) N ** I \(^\times\) N *

Average values indicating different letters are significantly different at \(p < 0.05\). Significance level: * \((p < 0.05)\), ** \((p < 0.01)\), *** \((p < 0.001)\).

4. Discussion

4.1. Effects of ISL and NAM on Crop Growth

The LAI and plant height are important indicators of crop growth and development. Previous studies have shown that crop growth was positively influenced by nitrogen availability and negatively affected by the water stress [33,34]. Experimental results in this study also illustrated that increasing quota per irrigation may improve significantly wheat LAI and height, because increasing quota means more water application, better soil moisture condition, more crop evapotranspiration, and a shorter period of water stress, which proved beneficial to plant growing [35]. Farooq et al. [36] stated that water and nitrogen deficiency results in a remarkable decrease in cell processes like cell division, cell elongation and cell elongation duration that cause reduction in leaf area. Experimental results also indicate that a reasonable distribution of all nitrogen among different growing stages is very important for achieving a good crop growth under a fixed total nitrogen application. Compared to the other two NAM treatments, N50:50 had the greatest LAI value in early stages, but the least in late stages, which suggests that distributing more nitrogen for topdressing in late stages is beneficial to winter wheat vegetable growth from the viewpoint of good LAI and plant height.

Aboveground biomass is a comprehensive indicator of the crop growth situation, because it is the united presentation of LAI, plant density, plant height, and also the material base of a good grain yield. The highest AB was obtained with the combination of ISL 50 mm and NAM N0:100, which implies that a sufficient ISL and NAM are essential to get better winter wheat growth, and these findings fit well with other researchers’ results [32,37,38].

4.2. Effects of ISL and NAM on Grain Yield

The most important objective of conducting this study was to quantify the appropriate ISL and NAM to enhance the grain yield. Irrigating the wheat crop as soon as the SWC reaches 35 mm has been proven as an optimal irrigation scheduling treatment to gain better grain yield, which is mainly due to greater yield components (especially number of grains per spike) and HI values under this specific treatment during the two growing seasons. This result corroborates well with the findings of Bhunia et al. [39], which showed that yield attributes like spike length, grain weight and number of grains per spike increased at optimum soil moisture rather than higher irrigation. Bandyopadhyay et al. [40] also stated that moderate deficit irrigation might increase the root growth and facilitate remobilization of reserve carbon to grains and accelerate grain filling, which could be responsible for improved grain yield under moderate deficit irrigation (SWC = 35 mm) as observed in our study.

Most yield components of winter wheat showed depressed results at ISL I20 and NAM N50:50, especially in term of grain number per spike, and resulted in reduced grain yield. These results are in accord with the findings of [9], who reported that wheat grain
yield is closely related to grain number and spikelets per spike. Irrigating the wheat with ISL 50 mm decreased the yield, showing that higher soil moisture may have negative effects on grain yield [32], because poor performance in yield components and very low values in harvest index may be the suitable explanation of why good aboveground biomass did not result in a good grain yield. The results are in line with the findings of other researchers [26,41], who reported that increasing the irrigation level enhances the grain yield up to a certain limit and then grain yield starts decreasing with increasing irrigation.

NAM also played a very important role in yield enhancement (Table 3). Our experimental results indicated that increasing appropriately the percentage of top-dressed nitrogen and applying more nitrogen at late stages is beneficial for achieving high yield in winter wheat, which is mainly due to the obvious improvement of aboveground biomass, number of grains per spike, 1000-grain weight. However, topdressing all nitrogen on drip-irrigated winter wheat is not the best NAM. Compared to applying 75% nitrogen as topdressing fertilizer, N0:100 decreased grain yield about 2.47% and 3.58% in the 2017–2018 and 2018–2019 growing seasons, respectively, which is because of 3.02% and 1.88% reductions in 1000-grain weight, and 6.63% and 7.41% decreases in grain number per spike in N0:100 during 2017–2018 and 2018–2019, respectively. The mean harvest index dropped from 0.53 for NAM N25:75 to 0.48 for N0:100 in the 2017–2018 season, and from 0.58 to 0.52 in the 2018–2019 season, which also explained why the greatest aboveground biomass did not result in the greatest grain yield under NAM N0:100. Similar results were reported by [42] where they alluded that reducing the basal dose and increasing nitrogen application at jointing and booting stages notably increased the yield components and, ultimately, the grain yield. However, less yield under excessive fertilization at late growth stages might have influenced the grain filling and decreased the yield by extending growth and delaying the maturity [3,43].

4.3. Evapotranspiration (ETc) and Water Use Efficiency (WUE)

The greater mean values of ETc in I50 treatment than those in I20 and I35 were due to better soil moisture, as irrigation amounts for I20, I35 and I50 were 60, 80, 110 mm and 100, 140, 200 mm during the 2017–2018 and 2018–2019 seasons, respectively. Furthermore, it was noticed that wetted depth was more stable at ISL I35 than those at I20 and I50 as crop growth behavior varied significantly under different ISLs, which might have created variation in water distribution and, ultimately, the ETc. During the growing season, it was observed that soil water content in I20 was reduced earlier than in other ISLs (Figures 6 and 7), which may be the main reason for the final ETc reduction in the ISL I20 treatment. The effects of NAM on ETc varied with different ISLs, and the ranges of ETc variation among different ISLs were relatively small. Besides, increment in ETc under N0:100 treatment might be attributed to more leaf area and biomass [44]. Dar et al. [45] reported that seasonal ETc increased with an increase in irrigation and nitrogen amount. Our results are in line with the findings of [46], who alluded that higher nitrogen-fertilized plots had 8% more ETc than non-fertilized plots.

Generally, WUE values in 2018–2019 were higher than those in 2017–2018, which might have been due to the synchronous effect of less precipitation during the 2018–2019 season that lowered total ETc (see Table 8), and the more suitable eco-environment in 2018–2019 that might have increased the grain yield (see Table 3). Results presented in Table 8 show that WUE increased with increasing the irrigation quota and the percentage of topdressing nitrogen up to some extent, and then decreasing them, which fitted well to some previous research [3,41]. Irrigating with ISL 135 and applying 75% nitrogen as topdressing resulted in the highest grain yield and medium crop evapotranspiration, which corresponded to the highest WUE in treatment 135N25:75.
Figure 6. Temporal changes in soil moisture (m$^3$/m$^3$) for various ISLs and NAM treatments during the 2018 wheat growing season.

Based on experimental data collected in two wheat seasons, the relationships between ETc and grain yield and WUE are plotted in Figure 8. Although grain yield lines and WUE lines in general show very similar trends during the two growing seasons, there were some differences between the variations of grain yield and WUE in detail. Under less ETc (or less irrigation), the grain yields increased very quickly, but the WUE slowly, and under greater ETc (or more irrigation), the WUE decreased more rapidly than grain yield. So it is
reasonable to suggest that over-irrigation during the winter wheat growing season may result in more water consumption, but not certainly result in higher grain yield and WUE under drip irrigation.

Figure 7. Temporal changes in soil moisture (m$^3$/m$^3$) for various ISLs and NAM treatments during the 2019 wheat growing season.
5. Conclusions

The results of a two-year study validated that irrigation scheduling and nitrogen fertilizer management extensively affected the wheat growth, grain yield and WUE. Based on the experimental results, some interesting points may be concluded: (1) More irrigation may improve winter wheat growth parameters but does not surely increase grain yield, which indicates that determining a suitable ISL is necessary for achieving high grain yield and WUE at the same time; (2) Increasing the percentage of topdressing nitrogen and applying by fertigation in late stages is beneficial to increase of grain yield and WUE, but topdressing all nitrogen in late stages is not the best nitrogen application mode under fixed total nitrogen application; (3) ISL I35 with NAM N25:75 is maybe the most suitable coupled irrigation and nitrogen combination for attaining synchronously high grain yield and water use efficiency in drip-irrigated winter wheat in the NCP. Otherwise, additional studies are required to further investigate the water and nitrogen movement, transformation, utilization, and losses in winter wheat fields. The studies are also required to evaluate the transferability of our study results to other soil and climatic conditions, which will be helpful for improving water and nitrogen management, and finally the sustainable development of winter wheat production in the North China Plain.

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