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Article

Effect of Nitrogen and Irrigation Application on Water Movement and Nitrogen Transport for a Wheat Crop under Drip Irrigation in the North China Plain

Juan Sui †, Jiandong Wang †,*, Shihong Gong †, Di Xu † and Yanqun Zhang †

State Key Laboratory of Simulation and Regulation of Water Cycle in River Basin,
China Institute of Water Resources and Hydropower Research Beijing 100048, China;
E-Mails: suijuan2003@163.com (J.S.); gshh@iwhr.com (S.G.); xudi@iwhr.com (D.X.);
zhangyq@iwhr.com (Y.Z.)

† These authors contributed equally to this work.

* Author to whom correspondence should be addressed; E-Mail: wangjd@iwhr.com;
Tel.: +86-10-68786583; Fax: +86-10-68451169.

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Abstract: For improving water scarcity and groundwater pollution from agriculture, two-year experiments (2011–2013) with three water levels (0.3, 0.5 and 0.8 evaporation (E) in 20-cm-diameter pans) and four nitrogen (N) levels (120, 140 and 190 kg·ha^{-1} in 2012 and 120, 190 and 290 kg·ha^{-1} in 2013) were conducted to study effects of water and N availability on water movement and N transport for a wheat crop under drip irrigation in the North China Plain. The results indicated that under drip irrigation, deep percolation at 1-m depth was stable at 0.5–0.8 E with the same N rate for winter wheat. At 0.5–0.8 E, deep percolation was also relatively stable with increasing N rate from 120 to 140 kg·ha^{-1} or from 190 to 290 kg·ha^{-1}. The irrigation schedule and N rates only affected N leaching below the root zone of winter wheat (60-cm depth), while the N residual in the soil layer presented more risk to the environment than N leaching. In general, the 290-kg-ha^{-1} N level was not recommended using drip fertigation for winter wheat in the North China Plain. The empirical equation given by the Ministry of Geology and Mineral Resources was also not recommended for estimating the drainage under drip irrigation.

Keywords: drip irrigation; irrigation; nitrogen; wheat crop; deep percolation; nitrogen leaching

1. Introduction

Water scarcity is the major constraint on crop production worldwide, especially in the North China Plain (NCP) [1–4]. As one of the main grain-producing areas in China, the NCP accounts for 30% of the national food production [5]. Winter wheat (*Triticum aestivum* L.) is a major crop in the region, primarily limited by seasonal rainfall [6]. Because the majority of precipitation comes after the wheat harvest, the annual precipitation cannot satisfy actual crop evapotranspiration (ET) of 800–900 mm during the wheat growing season [4,7]. Supplementary irrigation is thus necessary for wheat production in the NCP. Because of the lack of surface water, groundwater in the region has been seriously exploited for irrigation [8,9]. Although the excessive exploitation of groundwater resources leads to groundwater depression, flood irrigation is still the major irrigation method [10]. At present, the limited water resources have been unable to meet the needs of supplementary irrigation water fully in this region. Meanwhile, the farmers still believe that increasing nitrogen (N) fertilizer is the only way of obtaining high yields of wheat in the NCP. Indeed, the grain yield of wheat increased with increasing rates of fertilizer application, which were reported from a series of field experiments [11,12]. However, it is also found that the excessive application of nitrogen (N) cannot increase crop yields further, but considerably increases N leaching [13–15]. Overuse of fertilizer not only increased the high cost of production, but also led to degradation of water and soil quality, especially the groundwater [16–18]. A survey of groundwater nitrate-N (NO_3^--N) concentrations found that about 45% of 600 groundwater samples of the NCP exceeded the World Health Organization limit for NO_3^--N in drinking water of 50 mg·L^{-1}, with the highest NO_3^--N concentration reaching 113 mg·L^{-1} [4,19]. This illustrated that the deterioration of groundwater quality is now becoming serious due to the heavy use of nitrogen fertilizer in the NCP.

Fortunately, the problems of water scarcity and deterioration of groundwater quality could be moderated by the adoption of water saving strategies and optimization of N and water management practices. However, few studies have been conducted to assess the applicability of water saving strategies (*i.e.*, drip irrigation) for winter wheat in the NCP. Wang *et al.* (2013) reported that drip irrigation was recommended for winter wheat in the NCP due to improved yield and water use efficiency [20], but no further studies were conducted to access the effects of drip irrigation on deep percolation losses and NO_3^- leaching for winter wheat in the NCP.

As known from a series of field experiments in other regions, drip irrigation could reduce deep percolation losses of water and minimize NO_3^- leaching [21,22]. However, zero leaching loss of N is not likely to be possible in agricultural production [23]. Drip irrigation also cannot completely eliminate the deep percolation and leaching of N beyond the root zone [24,25]. Proper irrigation schedules and reducing the N rates could keep the leaching losses to a minimum [26]. For example, high irrigation frequency could reduce NO_3^- leaching and N rates had a significant effect on NO_3^- leaching under drip irrigation [5,25]. However, these experiments were conducted for sugarbeets, tomatoes and maize. There was still no experimental study about the effects of combining different irrigation and N fertilizer management strategies on deep percolation and NO_3^- leaching for winter wheat under drip irrigation in the NCP.

With these background considerations, a two-year field experiment was conducted in the NCP. It was assumed that N volatilization was zero, and we only considered plant N uptake, N residual and N leaching during the experimental periods. We focused on assessing the effect of different N and irrigation levels on water movement and N transport for the wheat crop under drip irrigation in the NCP. Two objectives were established in our study: (1) to examine the effect of different levels of N and irrigation on depth and time distribution of soil moisture and N under drip irrigation during the winter wheat seasons of the NCP and (2) to assess the effect of different levels of N and irrigation on deep percolation and NO_3^- leaching under drip irrigation in the NCP during the winter wheat growing season.

2. Materials and Methods

2.1. Experimental Site and Field Management

A replicated field experiment was conducted over two wheat growing seasons (2011–2012 and 2012–2013) at the Irrigation Experiment Station of the China Institute of Water Resources and Hydropower Research (39°37′ N, 116°25′ E, 30 m above sea level), which is located in the Beijing region of the NCP (Figure 1). Summer-dominant rainfall happens in this region, contributing more than 70% of yearly rainfall between July and September. The long term mean annual precipitation was 644 mm from 1951–2013, and the mean temperature was 12.2 °C. Near normal precipitation of 137 mm fell during the winter wheat-growing season (April–June) in 2012, and 98 mm fell in 2013, which was 26% less than the average of 133 mm over the last 60 years (Table 1). The precipitation in both years was significantly less than the average of 35 mm (1951–2013) in May (from stem-elongation to Development of fruit), when the crop was more sensitive to water stress [6,27]. The precipitation was also less than the average of 22 mm in April in 2013. The mean temperature over the growing season was 20.2 °C in 2012, which was 0.7 °C higher than the 19.5 °C long-term record (1951–2013), whereas the mean temperature of 18.2 °C in 2013 was 1.3 °C lower than the long-term record. The temperature was also lower in April and June of 2013 than the average maximum/minimum air temperatures of the last 60 years for the corresponding period. Mean daily 20-cm-diameter pan evaporation was 3.07 mm in 2012 (20 March–13 June) and 2.98 mm in 2013 (7 April–17 June). Full details of the experimental site and soil were provided in Wang *et al.* [20], and only details pertinent to this study are presented here. The soil at the experimental site was a silt loam, with organic matter content of 3.5 $g \cdot kg^{-1}$, field capacity of 0.31 $m^3 \cdot m^{-3}$, bulk density of 1.58 $g \cdot m^{-3}$ and permanent wilting point of 0.11 $m^3 \cdot m^{-3}$ (1 m depth).

Field management: Winter wheat (*Triticum aestivum* L. cv. Zhongmai 175) was sown on 3 October 2011 and 9 October 2012 using a sowing machine (Table 2). The row spacing was about 12.5–15 cm with seedling density of 450–800 $plants \cdot m^{-2}$. Irrigation was applied (75 mm) before sowing. At planting, N (as compound fertilizer, $N:P_2O_5:K_2O$ = 15%:15%:15%) was added at a rate equivalent to 83 $kg \cdot ha^{-1}$ to ensure germination and establishment. Wheat in the plots was harvested on 13 June 2012 and 19 June 2013. The field experiment began after the overwintering stage of winter wheat and the growing season of winter wheat was divided according to BBCH scale (Table 2) [28], *i.e.*, Tillering stages: 181 days after sowing (DAS) in 2012, 179 DAS in 2013; Stem-elongation stages: 205 DAS in 2012, 201 DAS in 2013; Inflorescence emergence, heading stages: 222 DAS in 2012, 215 DAS in 2013; and Development of fruit stages: 228 DAS in 2012, 222 DAS in 2013.

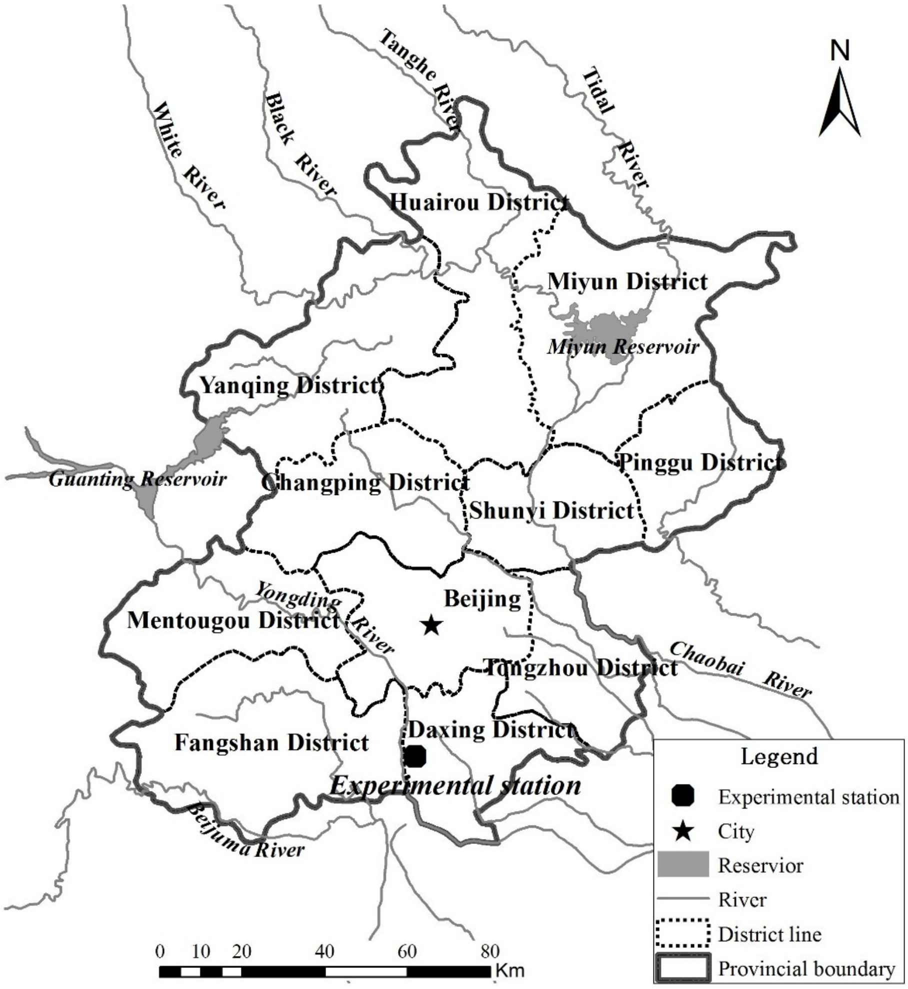

Figure 1. The location of the experimental station of the China Institute of Water Resources and Hydropower Research in the North China Plain is marked with a black dot.

Table 1. Monthly precipitation, average, minimum and maximum air temperatures (*P*, *T*, T_{min} and T_{max}, respectively) during the growing period (April–June) of experimental years 2012 and 2013 and long term averages (1951–2013) for the growth stages of winter wheat.

Month	2012				2013				Average (1951–2013)			
	P (mm)	T (°C)	Tmin (°C)	Tmax (°C)	P (mm)	T (°C)	Tmin (°C)	Tmax (°C)	P (mm)	T (°C)	Tmin (°C)	Tmax (°C)
April	58	15.0	8.2	21.1	3	11.6	4.6	18.1	22	13.9	7.8	20.2
May	7	21.5	14.0	28.2	3	20.6	13.8	26.7	35	20.3	13.9	26.6
June	72	24.0	18.3	30.2	92	22.5	18.1	27.4	76	24.4	18.8	30.4

Table 2. Data and days after sowing of different growth stages for winter wheat during the experiment in 2012 and 2013.

Year	Growth Stage											
	Sowing		Tillering		Stem-Elongation		Inflorescence Emergence, Heading		Development of Fruit		Harvesting	
	date	days	date	days	date	days	date	days	date	days	date	days
2011–2012	3/10	1	31/3	181	24/4	205	11/5	222	17/5	228	13/6	255
2012–2013	9/10	1	5/4	179	27/4	201	11/5	215	18/5	222	19/6	254

2.2. Experimental Design

Irrigations were scheduled according to the cumulative 20-cm-diameter pan evaporation (E) that had occurred since the previous irrigation. Three levels of water, viz., 0.8, 0.5 and 0.3 E (W_1, W_2 and W_3, respectively), were adopted and the cumulative irrigation amounts were 30, 40 and 30 mm before Stem-elongation, from Stem-elongation to Senescence, and after Senescence, respectively, in 2012 and 2013. When the cumulative pan evaporation reached the specified value for irrigation, supplemental irrigation started. The emitters (Netafim Ltd., Tel Aviv, Israel) were spaced 30 cm apart, with a 1.2 $L \cdot h^{-1}$ flow rate at 1 bar operating pressure.

Fertilizer application of 120–240 $kg \cdot ha^{-1}$ has been reported to sustain the high yield of winter wheat for traditional flood irrigation in the NCP [14], while the application of 290 $kg \cdot ha^{-1}$ is the local conventional level of fertilizer. In the present study, four levels of N were applied using fertigation under drip irrigation in the experiment: 120 $kg \cdot ha^{-1}$ (N_{120}, F_1), 140 $kg \cdot ha^{-1}$ (N_{140}, F_2), 190 $kg \cdot ha^{-1}$ (N_{190}, F_3) in 2012 and N_{120}, N_{190}, and 290 $kg \cdot ha^{-1}$ (N_{290}, F_4) were used in 2013 (Table 3). Based on the conventional fertigation scheme, N (as urea, 46%) was applied as topdressing on 10 April in 2012 and 2013, when winter wheat was irrigated at Tillering stage. During the experimental growth period of winter wheat of 2012, the amounts of irrigation water applied were 112, 70 and 42 mm at W_1, W_2 and W_3 levels, respectively (Table 3). In 2013, the amounts of water were 144, 90 and 54 mm at W_1, W_2 and W_3 levels, respectively. Since the interactive effects of N and water influenced the crop water uptake, the evaporative demands were different at different treatments. During the experimental growth period of winter wheat of 2012, the evaporative demands were 253, 248, 252, 239, 233, 235, 244, 213 and 206 mm at W_1F_1, W_1F_2, W_1F_3, W_2F_1, W_2F_2, W_2F_3, W_3F_1, W_3F_2 and W_3F_3 treatments, respectively (Table 3). In 2013, the evaporative demands were 221, 216, 222, 206, 189, 207, 187, 180 and 175 mm at W_1F_1, W_1F_3, W_1F_4, W_2F_1, W_2F_3, W_2F_4, W_3F_1, W_3F_3 and W_3F_4 treatments, respectively.

Field experiments were designed according to a completely randomized block design. Each treatment was replicated three times. The experimental area was 66 × 32 m with a fixed drip-irrigation system and divided into 27 equal plots of 20 × 3 m.

Table 3. Application of N, irrigation amounts and evaporative demands of different treatments for winter wheat cultivation in 2012 and 2013.

Treatments	Application of N ($kg\cdot ha^{-1}$)		Irrigation Amounts (mm)		Evaporative Demands (mm)	
	2012	2013	2012	2013	2012	2013
W_1F_1	120	120	112	144	253	221
W_1F_2	140		112		248	
W_1F_3	190	190	112	144	252	216
W_1F_4		290		144		222
W_2F_1	120	120	70	90	239	206
W_2F_2	140		70		233	
W_2F_3	190	190	70	90	235	189
W_2F_4		290		90		207
W_3F_1	120	120	42	54	244	187
W_3F_2	140		42		213	
W_3F_3	190	190	42	54	206	180
W_3F_4		290		54		175

2.3. Soil Sampling

To assess the soil water and N status, samples were taken from the 0–20, 20–40, 40–60, 60–80, 80–100 and 100–120 cm layers of the soil profile using a hand-held auger. For each plot, three samples were taken immediately prior to sowing, 1 day before an irrigation, 1 day following an irrigation and at harvest. Additional measurements were taken 1 day after a more than 20-mm-rainfall event in 2013. For each sample, the soil sample was divided into two sub-samples. One sub-sample was used to determine the NO_3^--N concentrations and the other sub-sample was used to determine the water content gravimetrically [29]. Twenty grams of air-dried soil were extracted with 50 mL of 1 $mol\cdot L^{-1}$ KCl, and the NO_3^--N concentrations were determined by an Auto Analyzer (colorimetric method; Bran + Luebbe, Hamburg, Germany) [5,30].

2.4. Deep Percolation

Method 1 (M1): During the experimental season, the deep percolation loss (*DP*) was estimated from the unsaturated hydraulic conductivity as a function of the prevailing moisture content and time period. The equation was thus described as [31]:

$$DP = q\Delta t = K\left(S_e\right)\Delta t \quad (1)$$

where q is the mean volumetric flux density ($mm\cdot day^{-1}$), Δt is the time period (days), and $K(S_e)$ is the unsaturated hydraulic conductivity at soil depth of 1 m, which was estimated by [32]:

$$K\left(S_e\right) = K_S S_e^{1/2}\left[1-\left(1-S_e^{1/2m}\right)^m\right]^2 \quad (2)$$

where K_s is the saturated hydraulic conductivity; m is the van Genuchten parameter, which is obtained from the soil moisture characteristic curve, and optimized using software RETC [32]; and S_e is the relative saturation, which is calculated by:

$$S_e = \frac{\theta - \theta_r}{\theta_s - \theta_r} \tag{3}$$

where θ is the soil water content ($cm^3 \cdot cm^{-3}$), θ_s is the saturated volumetric water content ($cm^3 \cdot cm^{-3}$) and θ_r is the residual volumetric water content ($cm^3 \cdot cm^{-3}$).

Method 2 (M2): According to the soil water balance of the whole experimental period, *DP* at 1-m depth was determined by [33]:

$$DP = P + I - ET - \Delta W - R \tag{4}$$

where *P* is the rainfall (mm), *I* is the irrigation (mm), ΔW is the change in soil water storage in the soil profile (mm), and *R* is surface runoff (mm), assumed to be zero as the plots had small preventive bands. *ET* is the evapotranspiration (mm), which is calculated as:

$$ET = ET_0 \times K_c \tag{5}$$

where ET_0 is the reference evapotranspiration, which is determined by the FAO Penman–Monteith method [33]. K_c is the crop coefficient, which was obtained for wheat from Allen *et al.* (1998) [33].

Method 3 (M3): The empirical equation was given by the Ministry of Geology and Mineral Resources and *DP* is estimated using a recharge coefficient (α) multiplied by the amount of irrigation (*I*, mm) for the region as follows [20]:

$$DP = \alpha I \tag{6}$$

where the coefficient (α) depends on soil texture and on the amount of total irrigation. The coefficient ranges from 0.1 for clay soil to 0.3 for sandy soil. Values of α were taken to be 0.1 for the amount of total irrigation ≤90 mm, 0.15 for irrigation between 90 and 250 mm, and 0.2 for irrigation ≥250 mm for the soils [6].

2.5. Nitrate N Loss Assessment

The ceramic suction cups were located at 60-cm and 1-m depth for each treatment to obtain the samples of soil solution [34]. Suction cups were collected weekly with additional extractions taken at 12 h after an irrigation or a more than 20-mm-rainfall event. When the extraction began, a vacuum pressure of 30 kPa was applied to each suction cup. Then the solution was extracted for 36 h and the soil solution samples extracted were sent to the laboratory to be frozen in a 50-mL polypropylene bottle. After the harvest, the soil solution samples were analyzed for NO_3^--N concentration using an Auto Analyzer (Bran + Luebbe, Germany) [5]. The NO_3^--N leaching losses (*LN*) were estimated from NO_3^--N concentration in the suction cups and the amount of deep percolation loss as [35]:

$$L_N = DP \times C_N \tag{7}$$

where C_N is the NO_3^--N concentration in the deep percolating water.

The calculated results were converted to $kg \cdot ha^{-1}$, and then summed over the experimental period.

2.6. Statistical Analyses

Statistical analysis was conducted at a significance level of 0.05. The two factors considered were irrigation level and fertilization. The analyses of variance with Duncan's *post-hoc* test were conducted to test the effect of different fertilization and irrigation treatments on experimental results. Statistical analysis was conducted using SPSS statistical software.

3. Results

3.1. Depth and Time Changes of Relative Soil Moisture

As one of the most important soil moisture parameters, the relative soil moisture is described as θ/θ_{FC} (θ_{FC} = moisture at field capacity). The temporal variations in the relative soil moisture as affected by different levels of N and irrigation during winter wheat seasons of 2012 and 2013 are presented in Figures 2 and 3. The relative soil moisture variations throughout the experimental seasons were significantly influenced by the depth and irrigation levels, but not by the N levels. Because of the preceding winter irrigation, the relative soil moisture was high in the period 180–192 DAS in 2012 and 183–196 DAS in 2013. Because the ET increased with plant growth, the relative soil moisture decreased gradually after the stem-elongation stages, especially among the treatments with W_2 and W_3 irrigation levels. Under all treatments, the relative soil moisture variations were larger in the shallow layers (0–60 cm), and diminished as the depth increased, *i.e.*, soil moisture variation was more prominent in the top 0–20-cm layer and less prominent in the 20–40-cm layer. Compared to the W_3 treatments, W_1 and W_2 treatments distributed more water in a greater depth of soil. In particular, minimal effects of irrigation on the soil moisture of the 40–60-cm layer were observed at the W_3 irrigation level in 2012 and 2013. A decline in the relative soil moisture of the 60–100-cm layer was observed during the experimental seasons for all treatments.

No significant differences in soil moisture were observed under W_1F_1, W_1F_2 and W_1F_3 treatments in 2012. Similarly, the N application rates had no significant impact on soil moisture at the W_2 and W_3 irrigation level treatments in 2012. The similar trend towards no significant effect of N levels on the soil moisture was also observed in 2013.

3.2. Deep Percolation

Cumulative deep percolation of water (*DP*) at 1-m depth was estimated from the soil hydraulic conductivity (M1), soil water balance (M2) and empirical equation (M3). The effect of different levels of N and irrigation on cumulative deep percolation during two wheat growing seasons is shown in Tables 4 and 5. The *DP* was significantly influenced by irrigation and N levels in loam soil during both experimental seasons. With the same N level, the *DP* rates estimated by M1 were significantly higher at W_1 and W_2 irrigation levels than that at W_3 irrigation level in both years. However, there was no significant difference in *DP* between W_1 and W_2 irrigation levels. This is because of the low volume of water applied during the W_3 irrigation schedule, whereby more soil moisture in the 80–100-cm layer was extracted by plant roots in the W_3 treatments. Under the same irrigation level, the *DP* decreased with increasing N levels in 2012 and 2013. In particular, the effect of different N levels on the *DP* was significant among W_3 irrigation schedule treatments in both years. Thus, the minimum *DP* rates of 119 and 52 mm were found at the W_3F_3 treatment in 2012 and the W_3F_4 treatment in 2013, respectively. Under W_1 and W_2 irrigation levels, the *DP* for F_1 treatments was significantly higher than that for F_3 treatments, whereas it had no significant difference with that for F_2 treatments in 2012. Similarly, under W_1 and W_2 irrigation schedules, the *DP* rate for F_1 treatments was significantly higher than that for F_3 and F_4 treatments, while no significant difference in *DP* was found between F_3 and F_4 treatments in 2013.

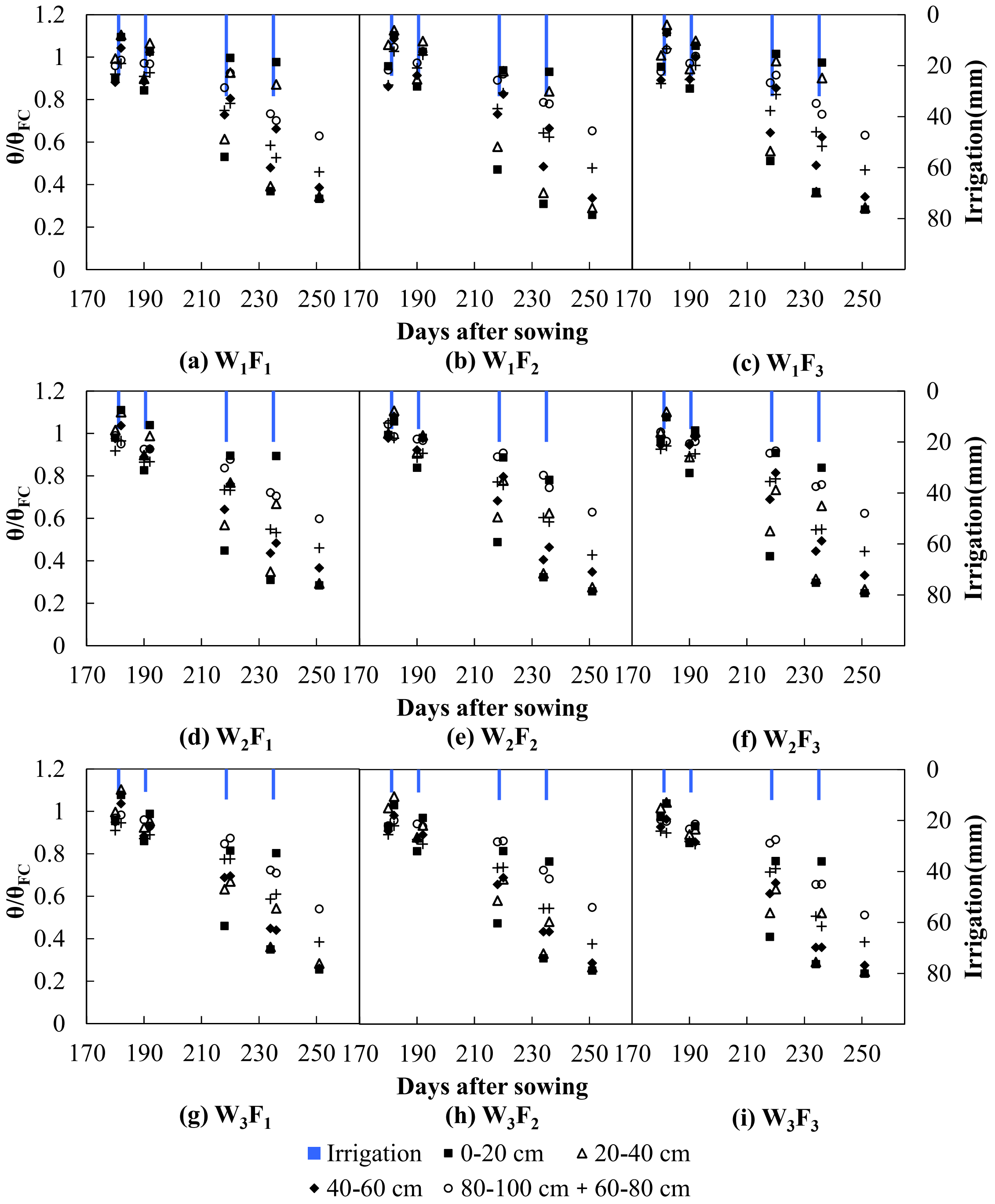

Figure 2. Temporal variation in relative soil moisture (θ/θ_{FC}) during the 2012 winter wheat growing season for nine treatments; W_1, W_2 and W_3: irrigations scheduled according to 0.8, 0.5 and 0.3 cumulative evaporation of 20-cm-diameter pan (E); F_1: N application at 120 kg·ha^{-1}, F_2: N application at 140 kg·ha^{-1} and F_3: N application at 190 kg·ha^{-1}.

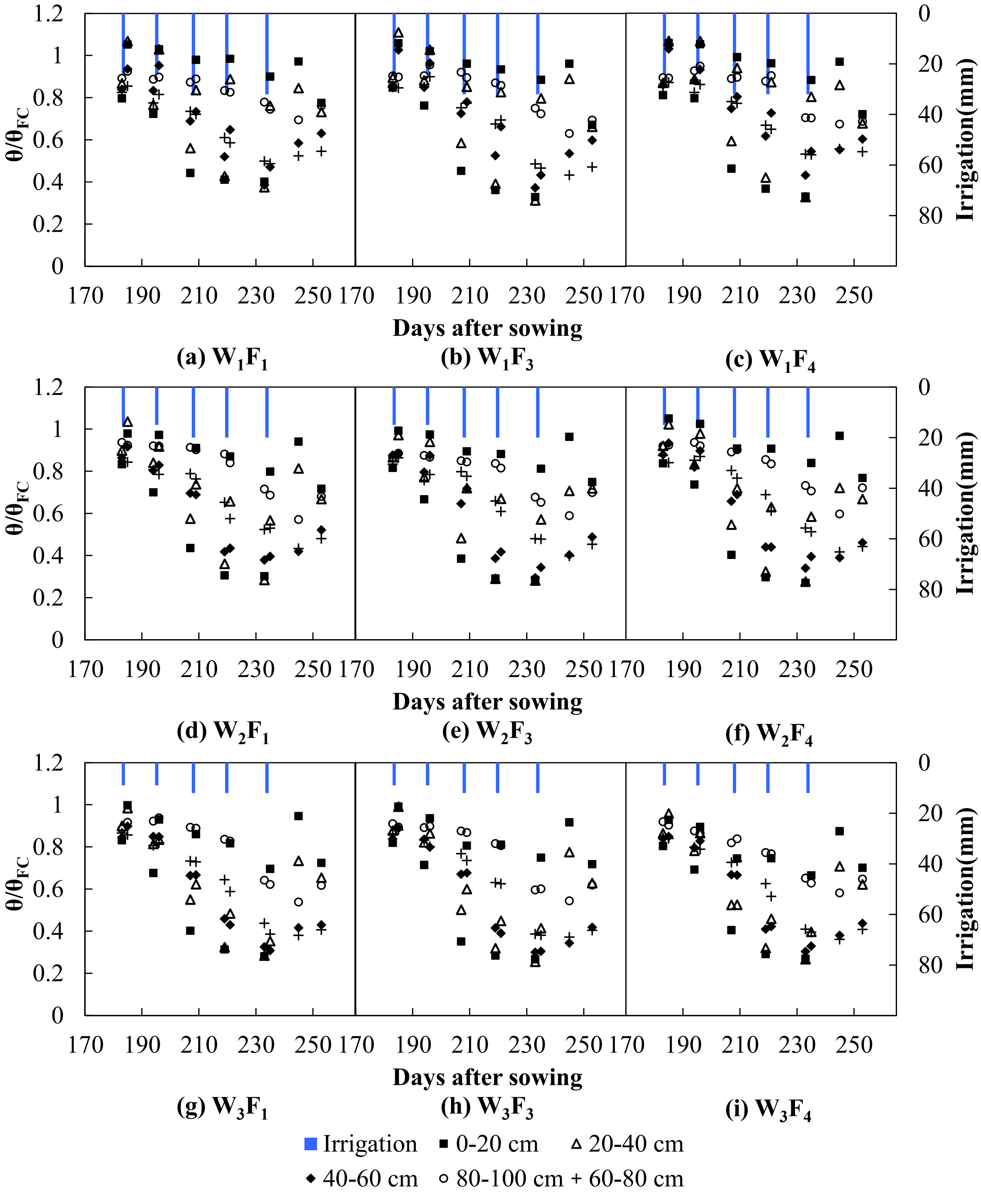

Figure 3. Temporal variation in relative soil moisture (θ/θ_{FC}) during the 2013 winter wheat growing season for nine treatments: W_1, W_2 and W_3, irrigations scheduled according to 0.8, 0.5 and 0.3 cumulative evaporation of 20-cm-diameter pan (E), respectively; F_1: N application at 120 kg·ha^{-1}; F_3: N application at 190 kg·ha^{-1}; and F_4: N application at 290 kg·ha^{-1}.

When the *DP* was estimated by soil water balance (M2), the trends, similar to the above results estimated by M1, were observed during the two experimental seasons. Compared with the *DP* estimated by M1, the *DP* losses estimated by M2 were significantly lower for all treatments in both years, *i.e.*, 39 mm lower at the W_1F_3 treatment in 2012. Compared with the *DP* estimated by M1 and M2, the *DP* losses estimated by the empirical equation (M3) were the lowest for all treatments in 2012. However, the *DP* estimated by M3 seemed to be higher in 2013 than the amounts in 2012, even though it was drier in 2013. There was higher deviation between the results calculated by M3 and the real *DP*.

Table 4. Deep percolation for all treatments during the wheat growing season of 2012.

Calculation Method	Deep Percolation (mm)								
	W_1F_1	W_1F_2	W_1F_3	W_2F_1	W_2F_2	W_2F_3	W_3F_1	W_3F_2	W_3F_3
M1	146	150	139	149	147	139	133	126	119
M2	101	105	100	114	112	97	93	93	85
M3	38	38	38	29	29	29	24	24	24
SE_m (W)	3.10			3.20			-		
LSD (W)	6.51			6.72			-		
SE_m (F)	3.10			3.20			-		
LSD (F)	6.51			6.72			-		

Notes: W_1, W_2 and W_3: irrigations scheduled according to 0.8, 0.5 and 0.3 cumulative evaporation of 20-cm-diameter pan (E), respectively; F_1: N application at 120 kg·ha^{-1}; F_2: N application at 140 kg·ha^{-1}; F_3: N application at 190 kg·ha^{-1}; M1: Method 1, M2: Method 2 and M3: Method 3; SE_m: standard error of means; LSD: least significant difference at 0.05 level of significance; "-" means there is no value.

Table 5. Deep percolation for all treatments during the wheat growing season of 2013.

Calculation Method	Deep Percolation (mm)								
	W_1F_1	W_1F_3	W_1F_4	W_2F_1	W_2F_3	W_2F_4	W_3F_1	W_3F_3	W_3F_4
M1	81	70	70	90	72	76	73	63	52
M2	40	36	33	38	33	29	31	26	23
M3	42	42	42	31	31	31	24	24	24
SE_m (W)	3.07			2.38			-		
LSD (W)	6.45			5.01			-		
SE_m (F)	3.07			2.38			-		
LSD (F)	6.45			5.01			-		

Notes: W_1, W_2 and W_3: irrigations scheduled according to 0.8, 0.5 and 0.3 cumulative evaporation of 20-cm-diameter pan (E), respectively; F_1: N application at 120 kg·ha^{-1}; F_3: N application at 190 kg·ha^{-1}; F_4: N application at 290 kg·ha^{-1}; M1: Method 1, M2: Method 2 and M3: Method 3; SE_m: standard error of means; LSD: least significant difference at 0.05 level of significance; "-" means there is no value.

3.3. Depth and Time Changes of NO_3^--N Concentrations

The temporal variations in NO_3^--N concentrations under different irrigation and fertilizer levels during the winter wheat seasons of 2012 and 2013 are presented in Figures 4 and 5. The figures show that the NO_3^--N concentration variations in soil layers during the experimental periods were significantly influenced by the depth, irrigation and N levels. Following the application of N as dissolved urea in water, the NO_3^--N concentration in the upper 0–40-cm increased steeply for all treatments on 192 DAS in 2012 and 185 DAS in 2013. The NO_3^--N concentration variation was more prominent in the top 0–20-cm layer and less prominent in the 20–40-cm layer in 2012 and 2013. In the 40–60-cm layer, the NO_3^--N concentration varied slightly during the growth periods of wheat in 2012 and 2013. The NO_3^--N concentration variation in the upper 0–60-cm layer was significantly influenced by irrigation levels in loam soil during two experimental seasons. The peak NO_3^--N concentration in the 0–20-cm layer, present on 192 DAS in 2012 and 185 DAS in 2013, increased significantly with decreasing irrigation level. With the same N level, the NO_3^--N concentration in the 20–60-cm layer was significantly higher at the W_1 irrigation level than the concentration at W_2 and W_3 during the 192–220 DAS in 2012 and 185–220 DAS in 2013. In the late growth period of 2013, the NO_3^--N concentration in the 0–20-cm layer was significantly higher at W_2 and W_3 than the concentration at W_1. There was no significant impact of irrigation levels on the NO_3^--N concentration in the 60–100-cm layer.

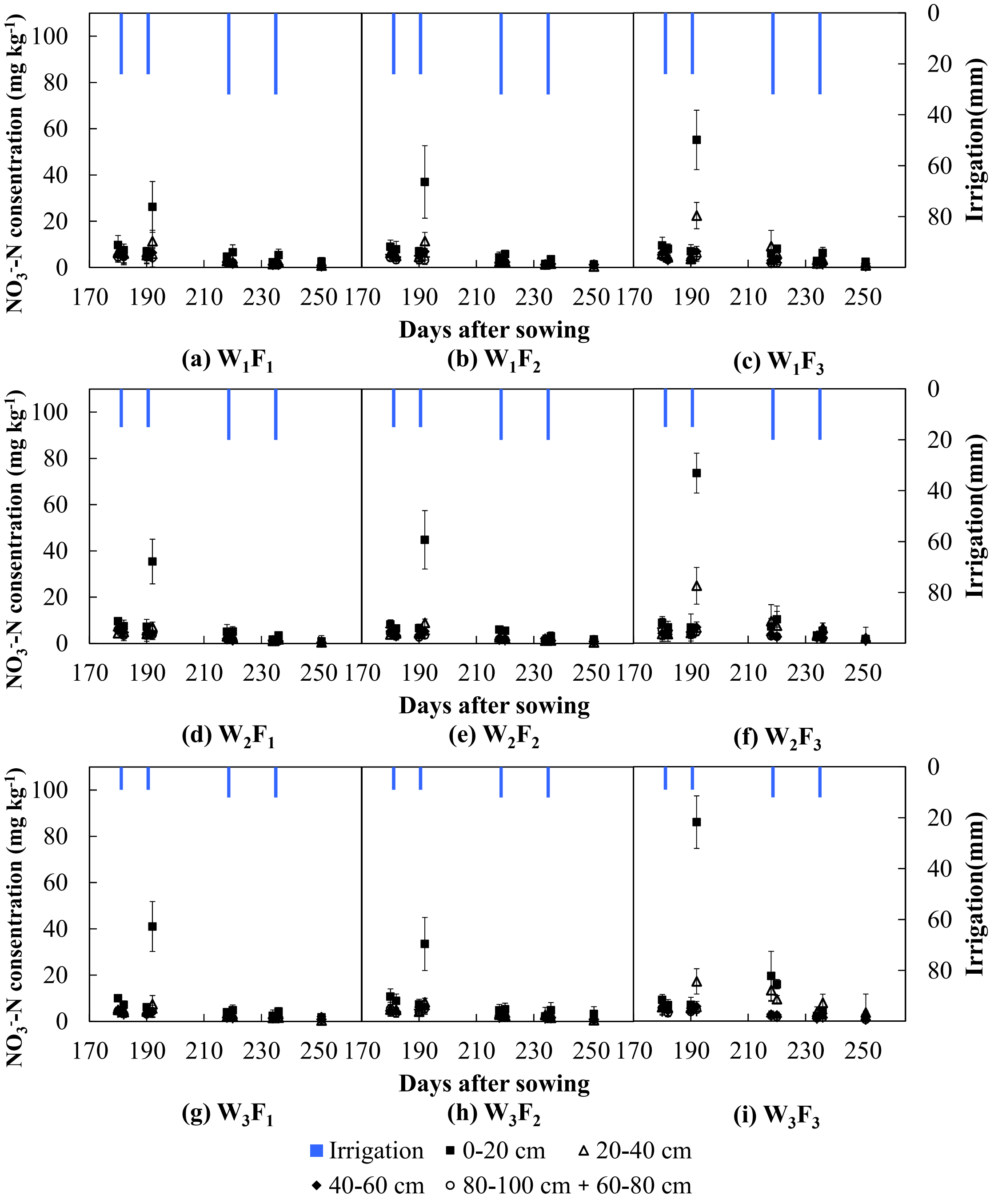

Figure 4. Temporal variation in the NO_3^--N concentration (mg·kg^{-1}) during the 2012 winter wheat growing season for nine treatments: W_1, W_2 and W_3, irrigations scheduled according to 0.8, 0.5 and 0.3 cumulative evaporation of 20-cm-diameter pan (E), respectively; F_1: N application at 120 kg·ha^{-1}; F_2: N application at 140 kg·ha^{-1}; and F_3: N application at 190 kg·ha^{-1}.

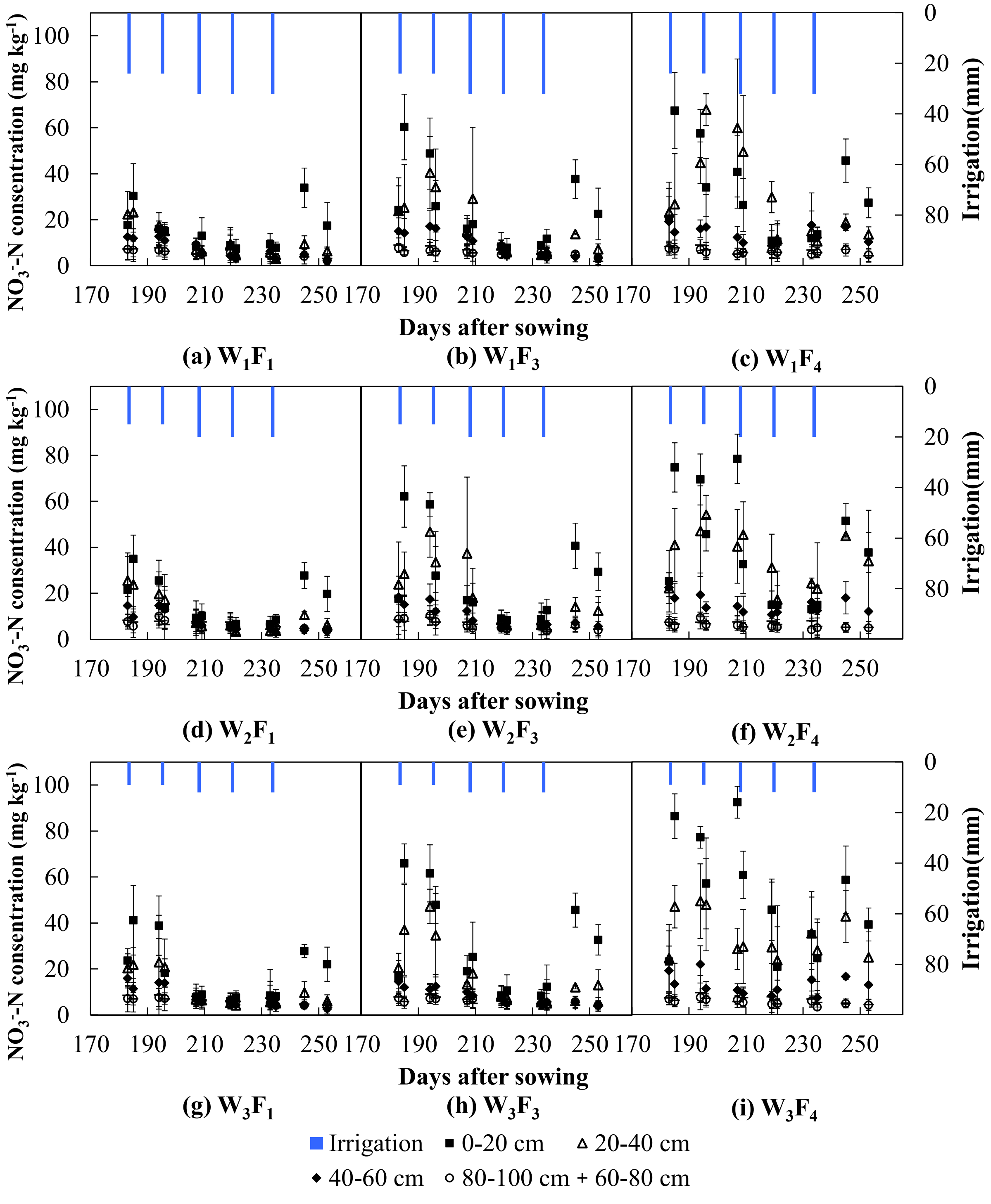

Figure 5. Temporal variation in the NO_3^--N concentration (mg·kg^{-1}) during the 2013 winter wheat growing season for nine treatments: W_1, W_2 and W_3, irrigations scheduled according to 0.8, 0.5 and 0.3 cumulative evaporation of 20-cm-diameter pan (E), respectively; F_1: N application at 120 kg·ha^{-1}; F_3: N application at 190 kg·ha^{-1}; and F_4: N application at 290 kg·ha^{-1}.

The NO_3^--N concentration in the 0–40-cm layer increased significantly with the increase in N level during the two experimental periods. At F_4 level, the NO_3^--N concentration in the 40–60-cm layer was obviously higher than the concentration at other levels in the late growth periods. Moreover, with the same irrigation level, the NO_3^--N concentration variation in the 20–40-cm layer at F_4 level was more significant than the changes at other N levels in 2013. There was no significant impact of N levels on the NO_3^--N concentration in the 60–100-cm layer during two experimental seasons.

3.4. NO_3^- Leaching and NO_3^- Residual

The seasonal N leaching was determined by deep percolation and N concentration in the soil solution. The NO_3^- leaching below the root zone (at 60 cm) and in the 100-cm soil layer were presented in Tables 6 and 7 during the two wheat seasons in 2012 and 2013. The results showed that the NO_3^- leaching below the root zone was significantly influenced by irrigation and N levels in 2012 and 2013. The uniform precipitation weakened the effects of irrigation levels on NO_3^- leaching in 2012, but the NO_3^- leaching at the 60-cm layer was still higher at W_1 and W_2 irrigation levels with the same N level than the amount at W_3. A similar trend was also observed in the dryer year of 2013. As expected, the NO_3^- leaching at 60 cm significantly increased with increasing N application level in 2012 and 2013. However, both irrigation and N levels had no significant impact on NO_3^- leaching at 100 cm in both years, even though the deep percolation at the 100-cm layer was significantly affected by different irrigation and N levels. The NO_3^- leaching at 100 cm seemed to be more affected by the initial N concentration in the soil in 2012 and 2013. Comparing to N leaching, more N was maintained in the 0–100-cm soil layer as N residual during the wheat crop seasons.

Table 6. Nitrate leaching (*NL*), initial nitrate concentration (N_{ini}) and nitrogen residual (*NR*) for all treatments during the wheat season of 2012.

Treatments	**W_1F_1**	**W_1F_2**	**W_1F_3**	**W_2F_1**	**W_2F_2**	**W_2F_3**	**W_3F_1**	**W_3F_2**	**W_3F_3**
NL at 100 cm layer (kg·ha^{-1})	21.5	21.6	23.9	29.5	22.6	31.2	21.1	26.2	27.3
N_{ini} at 100 cm layer (kg·ha^{-1})	14.7	13.8	15.3	19.7	14.8	19.0	15.0	18.0	18.8
Two-way analysis of variance									
Irrigation schedule	NS (p = 0.215)								
Nitrogen rate	NS (p = 0.337)								
NL at 60 cm layer (kg·ha^{-1})	14.7	16.0	18.5	16.9	16.5	23.6	11.0	12.4	20.6
N_{ini} at 60 cm layer (kg·ha^{-1})	17.3	17.1	19.5	17.9	16.7	13.4	14.0	14.1	18.3
Two-way analysis of variance									
Irrigation schedule	NS (p = 0.088)								
Nitrogen rate	* (p = 0.017)								
NR in 0–100 cm layer (kg·ha^{-1})	13.9	15.4	17.9	12.1	16.6	25.6	18.6	19.2	28.0
Two-way analysis of variance									
Irrigation schedule	* (p = 0.000)								
Nitrogen rate	* (p = 0.000)								
SE_m (W)	0.88								
LSD (W)	1.86								
SE_m (F)	0.88								
LSD (F)	1.86								

Notes: W_1, W_2 and W_3: irrigations scheduled according to 0.8, 0.5 and 0.3 cumulative evaporation of 20-cm-diameter pan (E), respectively; F_1: N application at 120 kg·ha^{-1}; F_2: N application at 140 kg·ha^{-1}; F_3: N application at 190 kg·ha^{-1}; NS: not significant at the 0.05 level; *: significant at 0.05 level of significance.

The N residual at 0–100-cm depth was significantly influenced by irrigation and N levels for the winter wheat crop in 2012 and 2013 (Tables 6 and 7). The N residual increased with the increase in N level, whereas it decreased with the increase in irrigation water level during two experimental seasons. No significant difference in N residual was found at W_1F_1, W_1F_2, W_2F_1 and W_2F_2 treatments, but significantly higher residuals were found at W_3F_1 and W_3F_2 in 2012. With the same N level, higher N residuals were observed at the W_3 level in 2013. With the same irrigation level, higher N residuals were also found at the F_3 and F_4 treatments in 2013. In particular, the highest N residual in F_4 treatments, observed in the 0–100 cm depth in 2013, may generate more nitrogen leaching during intensive rainfall events or heavy irrigation events after wheat harvest. The N residual in the 0–100-cm soil layer, averaged over all treatments, was 19 kg·ha^{-1} in 2012, which was clearly lower than the accepted residual N values of 50 kg·ha^{-1} in the 0–90-cm layer for many European countries [36]. However, due to the longer dry spells in 2013, the average N residual reached 175 kg·ha^{-1}, while the minimum N residual of 99.2 kg·ha^{-1} at the W_1F_1 treatment was also substantially higher than the accepted value of 50 kg·ha^{-1}.

Table 7. Nitrate leaching (NL), initial nitrate concentration (N_{ini}) and nitrogen residual (NR) for all treatments during the wheat season of 2013.

Treatments	W_1F_1	W_1F_3	W_1F_4	W_2F_1	W_2F_3	W_2F_4	W_3F_1	W_3F_3	W_3F_4
NL at 100 cm layer (kg·ha^{-1})	25.3	30.5	28.6	30.4	26.4	28.4	23.7	22.6	18.7
N_{ini} at 100 cm layer (kg·ha^{-1})	23.6	25.6	24.5	25.4	24.5	24.2	23.6	23.3	22.4
Two-way analysis of variance									
Irrigation schedule	NS (p = 0.073)								
Nitrogen rate	NS (p = 0.828)								
NL at 60 cm layer (kg·ha^{-1})	21.6	31.5	45.3	31.6	46.5	62.1	18.2	27.2	40.5
N_{ini} at 60 cm layer (kg·ha^{-1})	39.7	47.3	60.1	46.2	57.7	70.7	50.1	45.9	60.3
Two-way analysis of variance									
Irrigation schedule	* (p = 0.001)								
Nitrogen rate	* (p = 0.000)								
NR in 0–100 cm layer (kg·ha^{-1})	99.2	114.9	185.6	119.3	169.0	288.2	117.8	180.6	303.8
Two-way analysis of variance									
Irrigation schedule	* (p = 0.000)								
Nitrogen rate	* (p = 0.000)								
SE_m (W)	4.21								
LSD (W)	8.85								
SE_m (F)	4.21								
LSD (F)	8.85								

Notes: W_1, W_2 and W_3: irrigations scheduled according to 0.8, 0.5 and 0.3 cumulative evaporation of 20-cm-diameter pan (E), respectively; F_1: N application at 120 kg·ha^{-1}; F_3: N application at 190 kg·ha^{-1}; F_4: N application at 290 kg·ha^{-1}; NS: not significant at the 0.05 level; *: significant at 0.05 level of significance.

4. Discussion

4.1. Effects of Irrigation on Water Movement and N Dynamics

The loss of nitrogen from irrigation systems posed a serious threat to receiving water bodies [37], and probably caused a considerable increase in nitrate concentration in the groundwater [18]. Therefore, proper irrigation water management practices are needed that tactically allocate water and fertilizers to minimizing N leaching to groundwater [38]. As is well-known, there are differences between drip irrigation and flood irrigation practice. For example, wetting patterns from a drip irrigation emitter are usually considered as the radius of the wetted volume [39]. Drip irrigation can also maintain the desired concentration and distribution of ions and water in the soil [38], while minimizing leaching of N from the root zone of agricultural fields [24]. However, the application of water and N in excess of crop requirements contributes to the leaching of water and N below the root zone under drip irrigation. Therefore, optimal irrigation and fertilizer scheduling of drip irrigation is important to minimizing leaching of N from agricultural fields. A clear understanding of water and N dynamics in the soil is also important for the management of irrigation and fertigation under drip irrigation.

4.2. Movement of Water for a Wheat Crop under Drip Irrigation

As the results showed, irrigation increased the soil moisture at the surface layer gradually and the soil moisture was influenced by the depth and the irrigation amount (Figures 2 and 3), which was consistent with the results of previous studies [27,40]. In our study, the rate of N application did not significantly affect the variation in soil moisture (Figures 2 and 3), which was consistent with the results of Kong *et al.* [41]. On the other hand, the water movement was mainly influenced by the irrigation schedule under drip irrigation, which was similar to results of a previous study under flood irrigation [42]. This may be because the irrigation influenced the soil moisture directly, while the fertilizer only had minimal indirect effects on moisture [42]. Compared to the W_3 treatments, W_1 and W_2 treatments distributed more water in a greater depth of soil. This was consistent with the laboratory experimental results of Li *et al.* (2011), who showed that a higher irrigation level yielded a larger wetted depth [43]. However, our results further illustrated that the wetted depth was stable when the irrigation level was at 0.5–0.8 E for winter wheat in the NCP.

4.3. Distribution of NO_3^--N in Relation to the Movement of Water

As mentioned above, the NO_3^--N concentration variations in soil layers were significantly influenced by the depth and irrigation schedule, which was inconsistent with the results obtained by Behera and Panda (2009) in a semi-humid sub-tropical region [42]. Due to the high concentration of urea with limited irrigation water applied, the NO_3^--N concentration in the 0–20-cm layer increased significantly with the decrease in irrigation level (Figures 4 and 5). Because of the larger wetted depth under the higher irrigation levels, the NO_3^--N concentration in the 20–60-cm layer was certainly influenced by irrigation schedule (Figures 2–5). No significant difference in NO_3^--N in the 60–100-cm layer was found for all N and irrigation treatments under drip irrigation, which was different from the results of Cassel Sharmasarkar *et al.* (2001) under traditional flood irrigation [21]. In addition, The NO_3^--N concentration variation in the 0–60-cm layer was noticeably higher in 2013 than in 2012 under all treatments because of more dry spells during the period 183–239 DAS in 2013 (Figures 4 and 5, Table 1). The reason that the NO_3^--N concentrations were influenced by irrigation was mainly because transport of solute was the functions of convective and diffusive fluxes of water [44]. In this study, due to the higher urea concentration, higher N applications significantly increased the NO_3^--N concentration in the 0–40-cm layer and led to higher N residual in the root zone of wheat, which was similar with previous results of

Shi *et al.* (2012) [45]. Although the irrigation water and N residual were primarily maintained in the upper 60 cm under drip irrigation, it could not be conclude that there is no deep percolation and leaching of nutrients beyond the root zone in this study. Since the distribution of soil moisture and NO_3^--N concentration was affected by irrigation schedule and N application rate, the deep percolation and N leaching would be different under different irrigation and fertilizer treatments.

4.4. Deep Percolation at Different Levels of N and Water under Drip Irrigation

Deep percolation is considered to be one of the main factors determining the amount of N leached [46]. Matching irrigation rates with plant uptake ensures efficient water and N uptake while reducing deep percolation losses of water and nutrient [22]. In our study, deep percolation increased with increasing irrigation level, but decreased with increasing N application level under drip irrigation (Tables 4 and 5), which was similar to the results of Behera and Panda (2009) [42]. The reason for this may be because the soil water and N level affected the growth and amount of roots [47,48]. However, in our study, it was still found that the deep percolation for winter wheat in the NCP was stable at the range of water level from 0.5 E to 0.8 E for drip irrigation. Additionally, for the W_1 and W_2 irrigation schedules, no significant decrease in deep percolation losses were found between N application rates of N_{120}–N_{140} or N_{190}–N_{290}. This was mainly because root growth rate was mainly affected by soil water level and water flow could be enhanced only to roots exposed to high NO_3- levels [48]. The deep percolation was noticeably higher in 2012 than in 2013 under all treatments, possibly because of the higher precipitation in early growing season of 2012 (Table 1), when the roots of winter wheat were still fewer.

Deep percolation is difficult to measure in undisturbed soil conditions [49]. Indirect methods based on a detailed knowledge of soil water dynamics improved our ability to estimate deep percolation losses from cropping systems [25,42], while indirect methods based on the soil water balance were also widely used to estimate deep percolation losses [50]. The results illustrated that the deep percolation was underestimated using the soil water balance method (M2, Tables 3 and 4). This is probably because of underestimation of the water stress coefficient, as it is assumed that water can be stored in the root zone until field capacity is reached. The empirical equation (M3), which was assumed to only relate to the amount of irrigation, obviously neglected the effect of N levels and the precipitation distribution on deep percolation. In general, M3 was not recommended for estimating the deep percolation losses in the NCP under drip irrigation.

4.5. Risk of N Leaching at Different Levels of N and Water under Drip Irrigation

It is possible to control N leaching out of the root zone during the growing season with improved irrigation and fertilizer management. In our study, the N leaching at 60-cm depth was influenced by both irrigation schedule and N rates for the wheat crop under drip irrigation (Tables 6 and 7), which was similar to the findings of Behera and Panda [42], but inconsistent with the results of Sexton *et al.* (1998), who concluded that irrigation management is even more important than fertilizer management in reducing the N leaching losses [51].In addition, the results about N leaching at 100-cm depth illustrated that N leaching at 100-cm depth was not correlated to irrigation rate, N rate, or deep percolation for winter wheat in the NCP (Tables 6 and 7), which was similar with the results obtained by Allaire-Leung *et al.* in California [52]. From the above results, it could be concluded that more N was retained in the

0–100-cm soil layer under drip irrigation for winter wheat in the NCP. It was also found that the N residual increased with the increase in N application level and decreased with the increase in irrigation water level (Tables 6 and 7). As has been demonstrated, the potential risk of N leaching increased with the increase in residual N after the wheat season in the NCP. Under the treatments with W_3 irrigation rate, the N residual significantly increased. Likewise, when the N application was more than 190 $kg \cdot ha^{-1}$, the N residual significantly increased as well. Crop production in the NCP is the typical double-cropping systems (wheat/maize rotations) and N residual is likely to be reused in the next season of maize. However, the possibility for leaching with N rates of 290 $kg \cdot ha^{-1}$ was too high to be considered sustainable in the NCP. Because of the higher possibility of leaching, the N rate of 290 $kg \cdot ha^{-1}$ is not recommended in the NCP.

5. Conclusions

Field experiments (2011–2013) were conducted in the North China Plain to evaluate the effects of N and irrigation levels on water movement and N transport for winter wheat crop under drip irrigation. Results of this study suggested that the water and N levels only correlated N leaching below the root zone (60-cm depth) positively during the winter wheat crop seasons, owing to the irrigation water and N primarily maintained in the root zone under drip irrigation. The distribution of soil moisture was mainly affected by irrigation schedule, but deep percolation at 1-m depth was significantly influenced by irrigation rate and N application rate, while stable at water levels of 0.5–0.8 E with the same N application rate for winter wheat under drip irrigation. Additionally, at 0.5–0.8 E, deep percolation was also kept stable at N rates of N_{120}–N_{140} or at N_{190}–N_{290}. The empirical equation given by the Ministry of Geology and Mineral Resources seemed not to be appropriate for estimating the deep percolation of drip irrigation. Compared to the N leaching, the N residual in the 0–100-cm soil layer presented more risk to the environment under drip irrigation during the winter wheat seasons, but there is a need to further study the potential reuse of N residual during the next maize seasons. However, since the N residual was too high at 290 $kg \cdot ha^{-1}$, it is concluded that the N rate of 290 $kg \cdot ha^{-1}$ should not be recommended for use with drip fertigation for winter wheat in the North China Plain. Improving irrigation and fertigation programs for agriculture irrigated with drip irrigation systems may still need further field experiments to study and model estimates in the North China Plain.

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Author Contributions

The idea and approach for the study were designed by Jiandong Wang, Shihong Gong and Juan Sui. Juan Sui and Jiandong Wang performed the experiments and provided field data. All authors were involved in preparation of the manuscript.

Conflicts of Interest

The authors declare no conflict of interest.

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