agronomy

Article

Nitrogen Fertilization Effects on Soil Nitrate, Water Use, Growth Attributes and Yield of Winter Wheat under Shallow Groundwater Table Condition

Yingjun She [1,2], Ping Li [1,3], Zhenjie Du [1,3], Xuebin Qi [1,*], Shuang Zhao [1,2], Tong Li [1,2] and Wei Guo [3,*]

1 Farmland Irrigation Research Institute, Chinese Academy of Agricultural Sciences, Xinxiang 453002, China
2 Graduate School of Chinese Academy of Agricultural Sciences, Beijing 100081, China
3 Water Environment Factor Risk Assessment Laboratory of Agricultural Products Quality and Safety, Ministry of Agriculture and Rural Affairs, Xinxiang 453002, China
* Correspondence: qxb6301@sina.cn (X.Q.); guowei02@caas.cn (W.G.); Tel.: +86-373-339-3277 (X.Q.)

Abstract: Shallow groundwater plays a vital role in water use and the yield of winter wheat. Nitrogen (N) application significantly affects crop uptake and utilization of water from irrigation, but little is known about groundwater use. More importantly, excessive N application will also bring a series of environmental problems. An experiment was carried out in micro-lysimeters at 0, 150, 240, and 300 kg/ha N fertilization rates based on 0.6 m groundwater depth with relatively strong alkaline soil in the winter wheat growing season. The results showed that increasing the N application rate significantly increased the sensitivity of the daily groundwater evaporation velocity of winter wheat to environmental meteorological factors (soil surface moisture, humidity, atmospheric pressure and atmospheric temperature), and promoted crop water use, crop growth and yield under the 0.6 m groundwater depth. From 150 kg/ha to 300 kg/ha N fertilization, LAI and yield increased by 26.95–82.02%, and evapotranspiration (ET) and groundwater use efficiency (GUE) increased by 11.17–14.38%. However, a high N application rate would sharply induce surface soil drought, leading to a rapid increase in nitrate accumulation in the vadose zone and a significant decrease in partial factor productivity of applied N (PFPN). With the N application of 150–300 kg/ha, the accumulation of nitrate in the vadose zone increased by 8.12 times, and soil moisture in 0–20 cm and PFPN significantly decreased by 19.16–57.53%. N fertilization had a significant effect on water transfer and could promote the consumption and utilization of groundwater at 0.6 m depth. Considering yield, water use, the accumulation of nitrate, and PFPN, the optimal N application was 219.42–289.53 kg/ha at 0.6 m depth.

Keywords: daily groundwater evaporation velocity; evapotranspiration; meteorological factors; soil moisture; winter wheat; water use efficiency; yield

Citation: She, Y.; Li, P.; Du, Z.; Qi, X.; Zhao, S.; Li, T.; Guo, W. Nitrogen Fertilization Effects on Soil Nitrate, Water Use, Growth Attributes and Yield of Winter Wheat Under Shallow Groundwater Table Condition. *Agronomy* **2022**, *12*, 3048. https://doi.org/10.3390/agronomy12123048

Academic Editor: Junfei Gu

Received: 3 November 2022
Accepted: 29 November 2022
Published: 1 December 2022

1. Introduction

Groundwater is an important water source for human consumption and agricultural production [1,2]. In particular, shallow groundwater can rise through the soil capillary gap to supply crops, and can be absorbed and utilized by crop roots directly after being converted into soil water [3]. Shallow groundwater exists in many parts of the world [4]. Wheat is an important grain crop worldwide with sowing area accounting for about 20% in China [5]. Nitrogen (N) application significantly increased wheat yield and affected the water use of wheat [6,7]. However, an excessive amount of N application is not conducive to crop water use and yield formation, but will produce a series of environmental problems [8–10]. Therefore, the appropriate N application rate plays an important role in winter wheat growth, yield, and water use, especially shallow groundwater use.

Generally, the daily groundwater evaporation velocity (Gv), groundwater evapotranspiration (ETgw), evapotranspiration (ET), groundwater utilization rate (Gr), and water use efficiency (WUE) are important water indexes reflecting groundwater utilization (Gv, ET, Gr, and WUE mean the daily groundwater evapotranspiration of crop, crop evapotranspiration, the contribution proportion of ETgw in crop ET, the yield that can be produced per unit of water consumed, respectively). Liu et al. [11] found that winter wheat Gv decreased with the increase of groundwater depth at 0.5–2.5 m depth, with Gv exceeding 1.49 mm·d^{-1}. Babajimopoulos et al. [4] showed groundwater contribution to the root zone of maize to be about 3.6 mm·d^{-1} at 0.58 m depth. Yang et al. [12] found that Gr was the highest from the jointing to heading stage of winter wheat, which was 23.5% at the depth of 1.6–2.4 m. From Kahlown et al. [13] and Fidantemiz et al.'s [14] research, the ETgw of soybean, winter wheat and sunflower accounted for 72–90% of ET at the depth of 0.3–0.9 m, while sugarcane, berseem, and sorghum could not survive in these conditions. Gao et al. [15] showed that the Gr of summer maize was 65% under the condition of 1.0–1.5 m depth, and WUE was 2.02 kg/m^3 at 2.5–3.0 m depth. Deficit irrigation would increase Gv and WUE under a constant water table, and Gv was about 2.5 mm·d^{-1} from the jointing to maturity stage under severe deficit irrigation according to Huo et al.'s [16] report. It is clear that crop groundwater use is affected by several factors. However, it is interesting to note that as an important agricultural production measure, the effects of N fertilization on shallow groundwater use in winter wheat are rarely reported.

N application affects crop growth and water use, effectively improving crop yield. However, more N fertilization is not always better. Excessive N fertilization is not conducive to harmonizing soil nutrient composition [17,18], reducing soil texture and greatly increasing residual nitrogen, and decreasing N use efficiency in farmland [17,19–22], and ultimately limiting water use and yield [23]. The effects of proper N application on crop water use and yield have attracted much attention. For example, Zhou et al. [24] found that winter wheat yield and dry matter accumulation were under border irrigation with 240 kg N ha^{-1} higher than that under border irrigation with 300 kg N ha^{-1}. Si et al. [9] showed that drip irrigation with N application of more than 240 kg N ha^{-1} was not conducive to winter wheat growth and water use. Kumar et al. [25] reported that cotton N application of 225 kg N ha^{-1} with 600 mm irrigation resulted in better crop growth and yield in hot and arid areas; 210~270 kg N ha^{-1} with 140~215 mm irrigation was an efficient management mode, which could significantly increase yield, according to Ji et al. [26] and Sun et al.'s [27] findings. Cossani et al. [7] found that in contrast to the unfertilized conditions, in most cases the grain yield and WUE of crops increased with the increase of N supply. Naghdyzadegan Jahromi et al. [28] and Harries et al. [29] showed that the WUE of crops increased with the increase of N application rates under arid climate conditions. From these studies, it is not difficult to find that they mainly focused on the influence of N application on crop water use and yield under surface irrigation conditions. However, under shallow groundwater depth, the effect of N application on winter wheat growth attributes, WUE, yield, groundwater use of winter wheat, and nitrate content in the vadose zone remained unclear. Therefore, we used the lysimeter to plant winter wheat and control groundwater depth, and the objectives of our study were: (1) to explore the effects of N application on water use of winter wheat under the shallow groundwater depth, especially the use of groundwater; (2) to analyze the change of growth attributes, grain yield and nitrate accumulation under different N fertilization; and (3) to explore whether there is an appropriate N application rate under the condition of shallow groundwater depth.

2. Materials and Methods

2.1. Experimental Site

The experiment was carried out at the Agricultural Water and Soil Environment Field Scientific Observation and Experimental Station (latitude 35°27′ N, longitude 113°53′ E, elevation 73.2 m above sea level) of the Chinese Academy of Agricultural Sciences in Xinxiang, Henan Province. The local climate is continental and monsoonal, with an average rainfall of 588.8 mm. The mean annual temperature and potential evaporation were reported as 14.1 °C and 2000 mm, respectively. The meteorological data was obtained from a standard automatic weather station located in the experimental station. Meteorological factors during the test are shown in Figure 1.

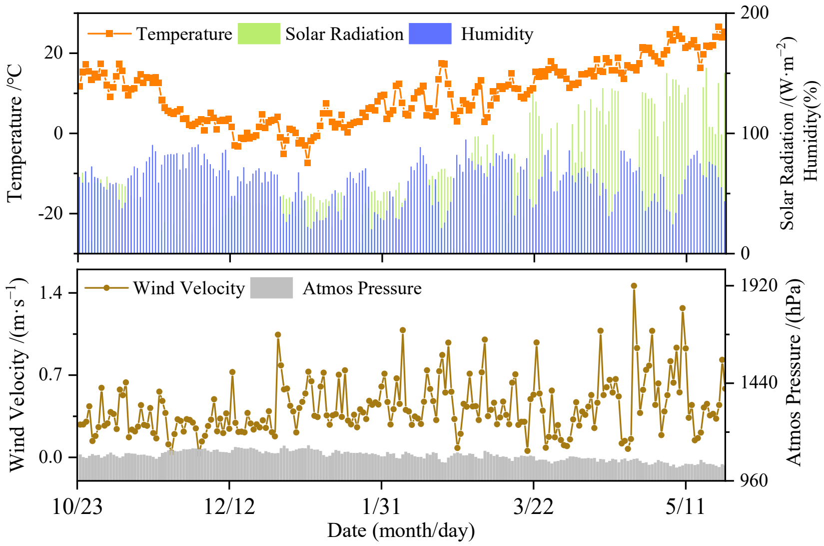

Figure 1. Meteorological factors during the test.

2.2. Experimental Design

2.2.1. Testing Apparatus

In this experiment, the self-developed lysimeters for planting winter wheat was used. The lysimeter was cylindrical with an outer diameter d = 40 cm and a wall thickness of 0.5 cm. The side wall of the lysimeter was slightly higher than the soil surface, 5–10 cm. The groundwater level control system adopted Mariotte bottles to supply water and maintain water levels. The bottom of the lysimeter was equipped with a back seepage filter layer to prevent leaking. The soil moisture probe (RS-WS-I20-TR, Shandong Rintech Measurement and Control Technology Co., LTD., data collection frequency was 1 h) was buried at 10 cm, 30 cm, and 50 cm depth from the soil surface, respectively. The Mariotte bottle was made of transparent plexiglass, with a height of 60 cm, an outer diameter of 11 cm, and a wall thickness of 0.4 cm. A 0–60 cm scale bar was pasted vertically with a precision of 1.0 mm to measure groundwater consumption (Figure 2).

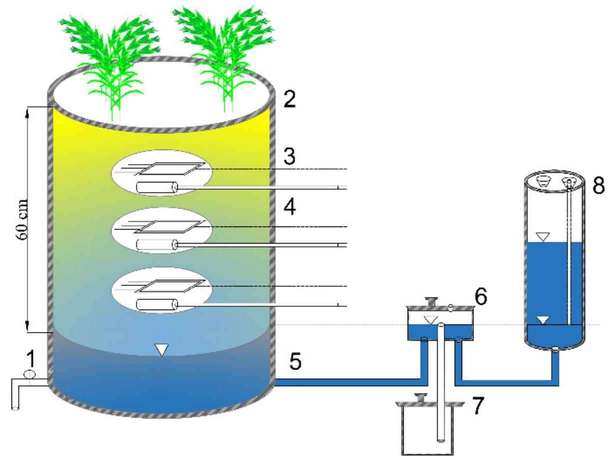

Figure 2. Schematic diagram of an experimental set-up; 1. Outfall; 2. Lysimeter; 3. TDR (Time Domain Reflectometry) probe; 4. Soil-solution extractor; 5. Inlet water pipe; 6. Water-table position and balancer; 7. Percolation bucket; and 8. Mariotte bottle.

2.2.2. Pre-Treatment of Experimental Soil

The test soil was taken from the local farmland, and the soil depth was divided into four parts: 0–20, 20–40, 40–60, and below 60 cm. After the back filter material was filled in the bottom of the lysimeter, the naturally air-dried soil was passed through a 5 mm sieve and backfilled in the order below 60, 40–60, 20–40, and 0–20 cm. During the backfilling process, the soil moisture probe was buried following the above method. The backfill bulk density was 1.40 g·cm^{-3}, compacted and filled in layers every 2 cm. Irrigation was performed from the top to form a complete soil structure after soil filling was completed. The soil was silty sandy loam, and the specific physical and chemical properties are shown in Table 1. The soil pH was determined in distilled water at a soil-to-solution mass ratio of 1:5 by the Thermo Scientific pH meter. The electrical conductivity (EC) of the soil extracts at a soil and water ratio of 1:5 (EC 1:5) was measured by a Leici-Shanghai DDB-303A conductivity meter. The soil organic matter (OM) was determined by the oxidation volumetric method for the determination of potassium dichromate, the available potassium (AK) of soil was measured by flame photometer, the alkaline nitrogen (AN) of soil was measured the alkalysis diffusion method, and the soil TN and TP were determined by a flow analyzer.

Table 1. Physical properties of the experimental soil.

Soil Layer (cm)	pH	EC (us·cm^{-1})	OM (g·kg^{-1})	AN (mg·kg^{-1})	AK (mg·kg^{-1})	TN (g·kg^{-1})	TP (g·kg^{-1})	Soil Texture		
								Clay (%)	Silt (%)	Sand (%)
0–20	9.34	270.00	12.29	17.27	128.33	0.85	0.63	18.26	47.43	34.31
20–40	9.62	313.33	9.87	13.30	81.33	1.25	0.59	18.09	45.93	35.97
40–60	9.58	364.00	8.78	7.93	81.67	1.52	0.53	17.84	44.04	38.78
>60	9.39	421.67	8.77	6.18	76.33	1.47	0.48	15.88	43.87	40.00

2.2.3. Description of Experiment

Based on the main root distribution of winter wheat in 0–60 cm [11], the groundwater depth was controlled at 0.6 m. Nitrogen (N) application treatments were set as no N fertilization treatment (NF0), Nitrogen application of 300 kg/hm^2 (the traditional N application rate [9,30,31]), reducing the nitrogen rate by 20% and 50% on the basis of the traditional nitrogen rate, respectively. The N application level was 0 kg/ha (NF 0), 300 kg/ha (3.77 g/lysimeter) (NF300), 240 kg/ha (3.01 g/lysimeter) (NF240), 150 kg/ha (1.88 g/lysimeter) (NF150), and each treatment was repeated three times. The experiment was a completely randomized block design.

Winter wheat (*Triticum aestivum L.*) was sown on 25 October 2020, with about 2.83 g/lysimeter, the cultivar was "Bainong 4199", and the budding was on 11 November 2020. Harvesting was performed on 22 May 2021, thus the whole growth period was 209 days. In the experiment, common urea (46% N), calcium magnesium phosphate (12% P_2O_5), and potassium sulfate (50% K_2O) were used as sources of N, P, and K fertilizers to supply 150 kg/ha P (1.88 g/lysimeter), 120 kg/ha K (1.51 g/lysimeter), and N according to N treatment rates. N fertilizer was applied in the form of base fertilizer and topdressing at a ratio of 6:4, with a mixture of 60% N, 100% P, and 100% K fertilizer applied at sowing stage, and 40% N fertilizer of topdressing applied at the jointing stage. During the whole experiment, a rain shelter was used to avoid precipitation interference. The irrigation date and amounts were based on the soil moisture from 0–40 cm and the crop growth process. The date and irrigation amounts were shown in Table 2.

Table 2. Winter wheat irrigation amount and irrigation date.

Irrigating Date (yy/mm/dd)	Irrigating Amount (mm)	Irrigating Date (yy/mm/dd)	Irrigating Amount (mm)
2021/1/13	17.64	2021/4/21	17.64
2021/3/17	30.88	2021/5/2	8.82
2021/3/31	17.64	2021/5/8	17.64
2021/4/11	17.64		

2.2.4. Monitoring Items and Analytical Methods

(1) Meteorological data

Solar radiation, humidity, atmospheric pressure, atmospheric temperature, and wind speed were obtained from the meteorological station of the test station (Figure 1).

(2) Crop height and leaf area index (LAI)

Three representative winter wheat plants were randomly selected in each lysimeter to measure crop height and leaf area ($n = 3$).

(1) Plant height: Before the booting stage, a ruler was used to measure the distance between the base of wheat and the highest point of leaf growth as the plant height, and the distance between the base of winter wheat and the top of spike (excluding awn length) was used as crop height in the booting stage and later. The measured growth stages were the regreening, jointing, booting, anthesis, filling, mid-filling and the maturity stage.

(2) LAI: The maximum leaf length and maximum leaf width were measured with a ruler. The leaf area index (LAI) was calculated by using the ruler method and the length-width coefficient method. The measured growth stages were the jointing, anthesis, filling and middle of filling stage.

(3) Nitrate-accumulation in the vadose zone

The soil sampling depth was 60 cm, and three soil samples were collected, corresponding to 0–20 cm, 20–40 cm and the 40–60 cm layer, respectively ($n = 3/lysimeter$). 10.0 g fresh soil samples were extracted with 0.01 mol/L $CaCl_2$ after wheat harvest and were analyzed for nitrate content using continuous flow analysis (Auto Analyzer-III from the bran-luebbeLuebbe, Germany) in the laboratory. Soil nitrate accumulation in the vadose zone was calculated using the method of Yang et al. [32].

(4) Soil moisture

The soil moisture of different soil layers in the lysimeter was derived from Shandong Renke Environmental monitoring platform V3.5.0 (Shandong Renke Measurement and Control Technology Co., LTD. Shandong, China).

(5) Daily groundwater evaporation velocity

The water level in the Mariotte bottle was recorded in the morning and evening. The groundwater evaporation of each growth stage and the whole growth period were calculated by daily groundwater consumption. The daily groundwater evaporation velocity (Gv, mm·d^{-1}) was calculated by the change in the number of Mariotte bottles Δh every day.

(6) Crop water requirements

Generally, irrigation should be needed when soil moisture (θ) is 60% of field water capacity (θ_f). Crop water requirements (Wr) can be obtained if soil moisture is capped at 75% of field water capacity. Based on the 0–20 cm soil moisture, the Wr of 0–20 cm was calculated by the equation:

$$Wr = (75\%\ \theta_f - \theta) \times 20 \times 10 \quad (1)$$

(7) Evapotranspiration (ET)

The water consumption of winter wheat during the growing period was calculated by the water balance method [14,33].

$$ET = P + I + ETgw - (D + \Delta W) \quad (2)$$

where the ΔW is the change of soil water storage, mm. I, irrigation amount, mm; P, precipitation, mm; ETgw, groundwater evaporation, mm; ET, evapotranspiration of crops, mm; D, the loss of deep leakage, irrigation was controlled during the experiment, and no deep leakage was caused during the whole growth period, mm.

(8) Crop water use efficiency (WUE), partial factor productivity of applied N (PFPN), groundwater use efficiency (GUE), and groundwater utilization rate (Gr)

Crop water use efficiency (WUE, g·m^{-3}) is the ratio of winter wheat grain yield (Y, kg/ha) to crop water evapotranspiration per unit area (ET, mm):

$$WUE = 100 \times Y/ET \quad (3)$$

Groundwater use efficiency (GUE, g·m^{-3}) is the ratio of winter wheat yield Y to groundwater evaporation (ETgw, mm):

$$GUE = 100 \times Y/ET_{gw} \quad (4)$$

Groundwater utilization rate (Gr, %) is the contribution proportion of ETgw in crop ET, which is used to quantitatively evaluate the influence degree of groundwater depth on crop water requirements under specific soil and crops [34].

$$Gr = 100 \times ET_{gw}/ET \quad (5)$$

Partial factor productivity of applied N (PFPN, kg·kg^{-1}) is an important index reflecting the comprehensive effects of soil's basic nutrient level and N application rate (N, kg/ha) [35,36].

$$PFPN = Y/N \quad (6)$$

2.3. Statistical Analysis

SPSS 23.0 (SPSS Inc. Chicago, IL, USA) was used for data analysis and we used ANOVA to test the difference in the grain growth attributes, yield, Gv, WUE, soil moisture, ET, GUE, and nitrate accumulation. Correlation analysis was conducted to relate the Gv with the meteorological factors, and grain yield with growth attributes, nitrate accumulation, water use and PFPN. All figures were created using Origin 2021 (OriginLab Corp., Northampton, MA, USA).

3. Results

3.1. Crop Height and Leaf Area Index (LAI)

Crop height and LAI of winter wheat increased with the increases of N application rate, which were significantly higher under N application than without N application. The crop height of NF300 treatment was significantly higher than that of NF150-NF240 treatment at the regreening stage, which was 17.98% and 12.82% higher, respectively (Figure 3a). Compared with NF150 treatment, the LAI of NF240 and NF300 treatment significantly increased by 35.45–107.23% and 58.75–169.98% at the anthesis stage and the mid-filling stage, respectively (Figure 3b).

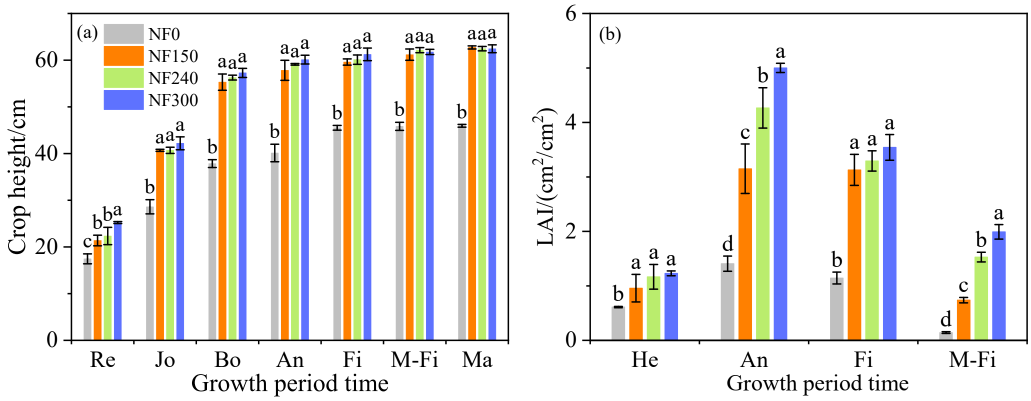

Figure 3. Crop height (**a**) and LAI (**b**) of winter wheat under different N application at 0.6 m groundwater depth. Re: the Regreening stage; Jo: the Jointing stage; Bo: the Booting stage; He: the Heading stage; An: the Anthesis stage; Fi: the Filling stage; M-Fi: the middle of filling stage; Ma: the maturity stage. NF0: N fertilization rate of 0 kg/ha; NF150: N fertilization rate of 150 kg/ha; NF240: N fertilization rate of 240 kg/ha; NF300: N fertilization rate of 300 kg/ha. Different letters represent significant difference at $p < 0.01$ level.

3.2. Yield and Nitrate Accumulation in the Vadose Zone

The yield and nitrate accumulation in the vadose zone increased significantly with increasing N application rate, but with the addition of N fertilization, the yield increase rate was obviously different from the nitrate accumulation rate in the vadose zone (Figure 4). With the N fertilization of 0–150 kg/ha, the yield and nitrate accumulation of NF150 treatment increased by 2.78 times and 24.19% of those of the NF0 treatment. From the N fertilization of 150–300 kg/ha, compared with NF150 treatment, the yield of the NF300 treatment increased by 26.95%, with a lower increase rate, while nitrate accumulation of the NF300 increased by 8.12 times, with a sharp increase rate.

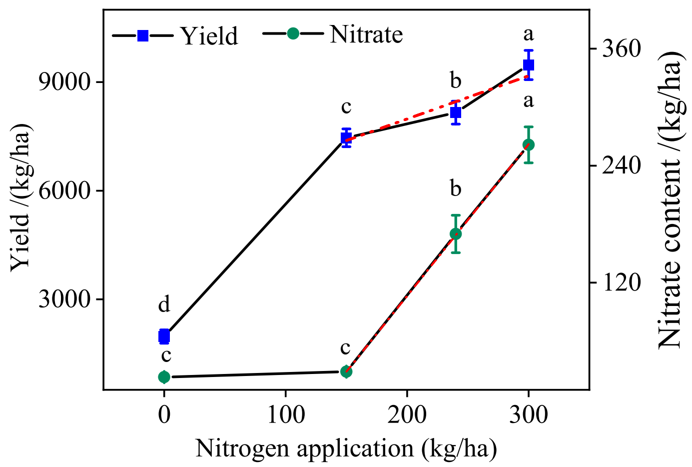

Figure 4. Winter wheat yield and nitrate accumulation in the vadose zone.

3.3. Daily Groundwater Evaporation Velocity (Gv), Maximum Gv and Average Gv in Each Growth Period

The Gv increased slightly in the greening stage, then started to increase at the jointing stage, reached the maximum from the jointing to the filling stage, and decreased at the end of the filling to the maturity stage. The Gv fluctuated more greatly in the regreening to the maturity stage from NF150-NF300 treatment than that from NF0 treatment (Figure 5a, b). Irrigation obviously decreased the subsequent Gv (Figure 5a). The Gv of N application treatment was significantly higher than that of NF0 treatment in each growth stage. With the advance of the growth process, the Gv increased with the N application rate added. From the anthesis to the filling stage, NF300 treatment was significantly higher than NF150-NF240 treatment, which was 4.82–14.65% higher on average. During the whole growth period, the Gv was as follows: NF300 > NF150-NF240 > NF0, and NF300 treatments were 14.75%, 13.22%, and 116.81%, which are significantly higher than that of NF240, NF150, and NF0, respectively. The law of the maximum Gv was similar to average Gv in each stage under N application (Figure 5c).

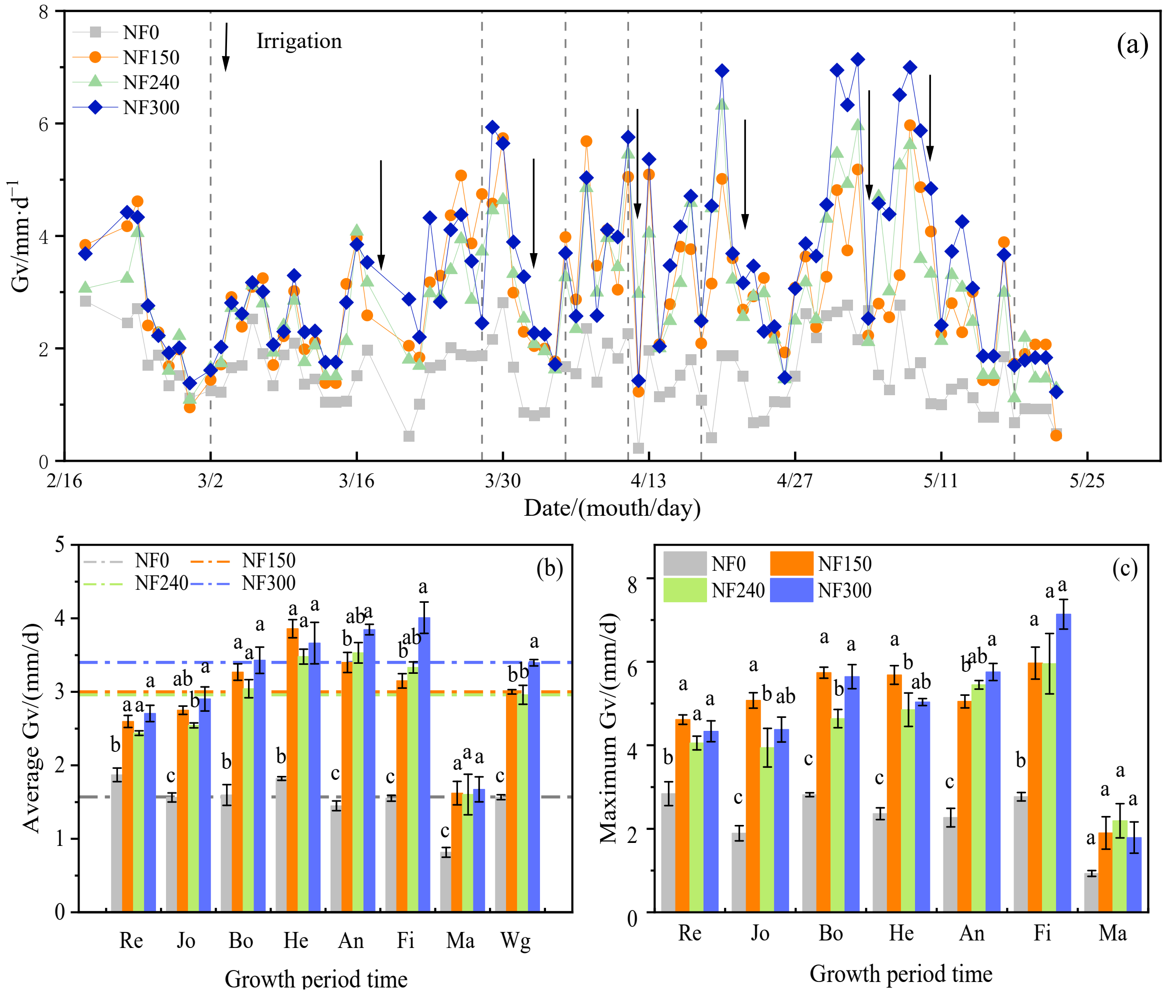

Figure 5. Daily groundwater evaporation velocity (**a**), Gv of every growth period (**b**), and the maximum Gv of every growth period (**c**) of winter wheat. Re: the Regreening stage; Jo: the Jointing stage; Bo: the Booting stage; He: the Heading stage; An: the Anthesis stage; Fi: the Filling stage; Ma: the maturity stage; Wg: the whole growth period; Gv: Daily groundwater evaporation velocity. From the onset of regreening stage, the various growth stages of winter wheat were indicated between the dashed lines in (**a**). The line in (**b**) represented the average value under the treatments. NF0: N fertilization rate of 0 kg/ha; NF150: N fertilization rate of 150 kg/ha; NF240: N fertilization rate of 240 kg/ha; NF300: N fertilization rate of 300 kg/ha. Different letters represent significant difference at $p < 0.01$ level.

3.4. Soil Moisture and Crop Water Requirements of 0–20 cm Soil Layer in Each Stage

Under NF150-NF300 treatment, the soil moisture in the 0–20 cm soil layer reached the maximum at the jointing stage, then gradually decreased and fluctuated greatly during the growth period at the booting to the maturity stage; NF150 treatment was significantly higher than NF240-NF300 treatment, which increased by 14.89–22.49% and 13.28–29.16%, respectively. Under NF150-NF300 treatment, the average soil moisture of fluctuation in the 40–60 cm soil layer was small, and the 20–40 cm soil layer was the smallest from the regreening to the maturity stage (Figure 6a–c). Water requirement (Wr) was the largest at the filling stage, while the rest of the growth stages were small. Wr of NF240-NF300 treatments was significantly higher than NF150 treatments, with an average increase of 153.16% and 163.03% (Figure 6d).

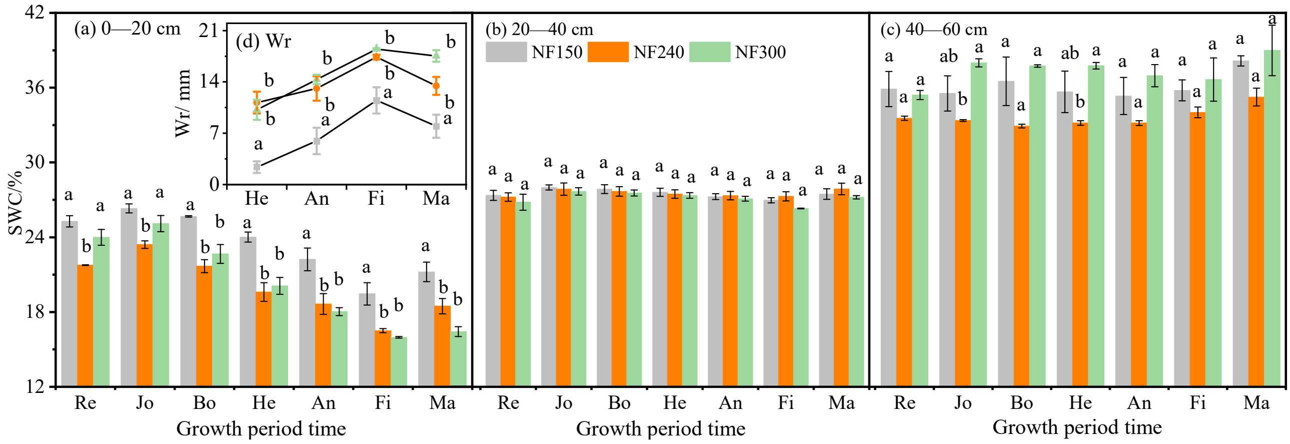

Figure 6. Soil moisture in 0–20 cm (**a**), 20–40 (**b**), and 40–60 cm (**c**) and water requirement of 0–20 cm soil layer (**d**) at different growth stages. SWC: soil moisture; Re: the Regreening stage; Jo: the Jointing stage; Bo: the Booting stage; He: the Heading stage; An: the Anthesis stage; Fi: the Filling stage; Ma: the maturity stage; Wr: water requirement. NF150: N fertilization rate of 150 kg/ha; NF240: N fertilization rate of 240 kg/ha; NF300: N fertilization rate of 300 kg/ha. Different letters represent significant difference at $p < 0.01$ level.

3.5. Evapotranspiration (ET), Groundwater Evaporation (ETgw), and Groundwater Utilization Rate (Gr)

The accumulative groundwater replenishment in the growth period was the highest in the filling stage, followed by the jointing stage and the regreening stage (Figure 7a). N application was significantly higher than that of NF0 treatment, which increased by 45.44–134.82%, 27.56–147.70%, and 46.35–166.17% under NF150-NF300 treatments, respectively. NF300 treatments were significantly higher than NF150-NF240 treatments in the anthesis to the filling stage, which increased by 13.35–26.98% and 7.46–19.92%. ETgw and ET under N application treatment were significantly higher than those under NF0 treatment (Figure 7b), which increased by 86.15–106.60% and 48.50–67.08%. NF300 treatment was significantly higher than NF150-NF240 treatment, in which ETgw and ET increased by 10.99–11.17% and 8.16–12.51%. Gr was 66.57–69.36% and was not significantly different under NF150-NF300 treatment but significantly higher than that under NF0 treatment, increased by 20.29–23.78% under NF150-NF300 treatment (Figure 7b).

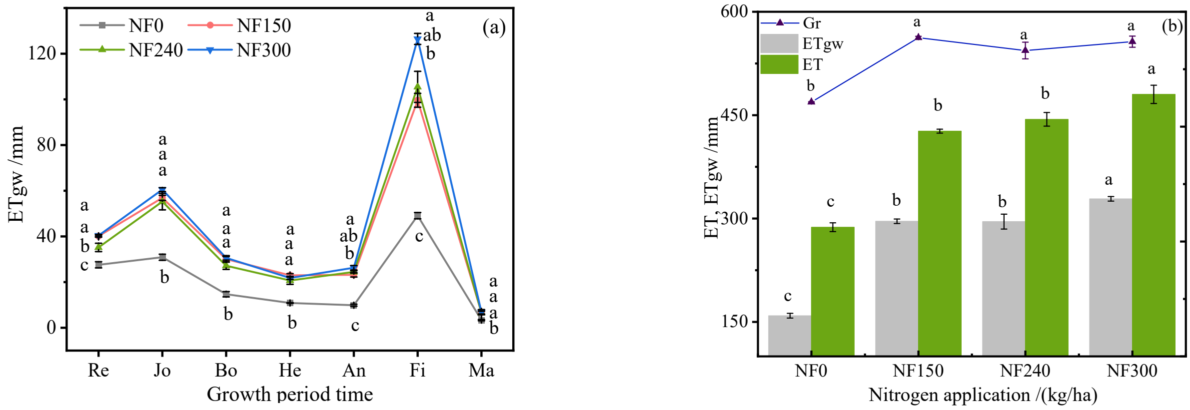

Figure 7. ETgw of each growth stage of winter wheat (**a**); ET, ETgw, and Gr of winter wheat (**b**). ETgw: groundwater evapotranspiration; ET: evapotranspiration; Gr: groundwater utilization rate; Re: the Regreening stage; Jo: the Jointing stage; Bo: the Booting stage; He: the Heading stage; An: the Anthesis stage; Fi: the Filling stage; Ma: the maturity stage. NF0: N fertilization rate of 0 kg/ha; NF150: N fertilization rate of 150 kg/ha; NF240: N fertilization rate of 240 kg/ha; NF300: N fertilization rate of 300 kg/ha. Different letters represent significant difference at $p < 0.01$ level.

3.6. Groundwater Use Efficiency (GUE), Water Use Efficiency (WUE), and Partial Factor Productivity of Applied N (PFPN)

GUE and WUE increased with the increase of N application, and N application was significantly higher than that of the NF0 treatment (Figure 8a). The GUE and WUE of NF150-NF300 treatments were 103.25–132.47% and 154.71–187.55% higher than the NF0 treatment. The NF300 treatment was significantly higher than the NF150-NF240 treatment; the GUE and WUE under NF300 treatment were 4.33–14.38%, 7.36–12.89% higher than those of NF150-NF240 treatment, respectively. PFPN decreased with the increase in N application rate (Figure 8b), and NF150 was significantly higher than NF240-NF300, which increased by 46.36% and 57.53%.

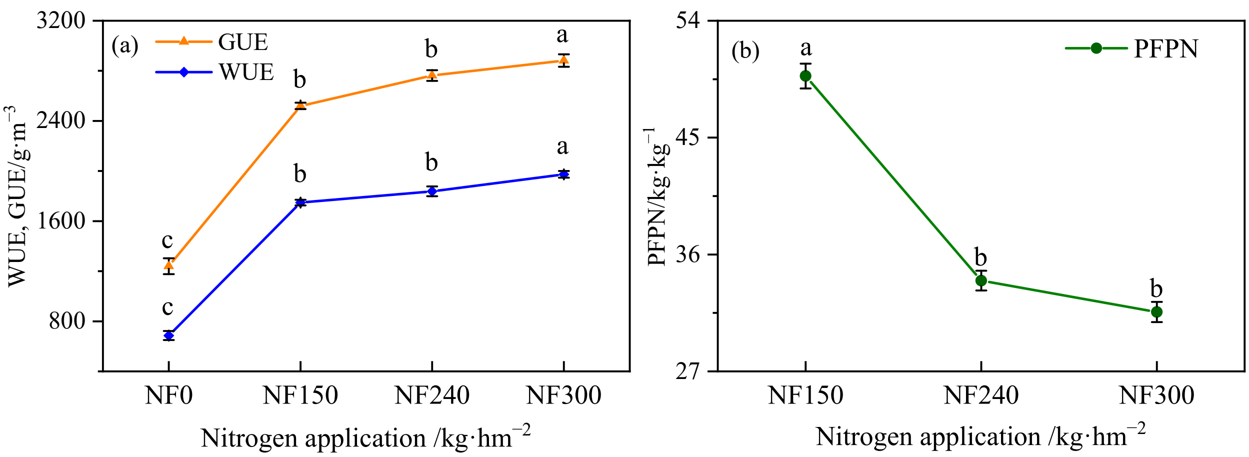

Figure 8. Changes in GUE, yield, WUE (**a**) and PFPN (**b**) with N application rate. Crop groundwater use efficiency (GUE), water use efficiency (WUE), and Partial factor productivity of applied N (PFPN). NF0: N fertilization rate of 0 kg/ha; NF150: N fertilization rate of 150 kg/ha; NF240: N fertilization rate of 240 kg/ha; NF300: N fertilization rate of 300 kg/ha.

3.7. Correlation Analysis

Groundwater evaporation velocity (Gv) was negatively correlated with soil surface moisture, humidity, and atmospheric pressure significantly, which increased with increasing N application rates. Gv was positively correlated with atmospheric temperature, and the correlation reached a significant level in the NF240-NF300 treatment

(Table 3). Grain yield, Gv, ETgw, ET, WUE, crop height, LAI, and nitrate accumulation were significantly positively correlated, while PFPN was significantly negatively correlated with yield, WUE, crop height, LAI, and nitrate accumulation (Figure 9a). These results indicated that N application increased winter wheat yield by increasing groundwater use and crop growth attributes.

GUE, WUE, and Gr showed a significant quadratic relationship with the N application rate, R^2 = 0.82–0.98 (Figure 9b). When the N application rate was 219.42–289.53 kg/ha, Gr, GUE, and WUE reached the maximum, which were 69.15%, 2863.91 g·m^{-3}, and 1942.78 g·m^{-3}, respectively.

Table 3. Correlation between daily groundwater evaporation velocity and environmental factors at different N application rates.

NF	Soil Surface Moisture (cm^3·cm^{-3})	Current Solar Radiation (W·m^{-2})	Cumulative Solar Radiation (MJ·m^{-2})	Humidity (%)	Dew Point Temperature (°C)	Atmos Pressure (hPa)	Temperature (°C)	Highest Wind Velocity (m·s^{-1})	Wind Velocity (m·s^{-1})
NF0	−0.284 *	−0.033	−0.016	−0.263 *	−0.382 **	0.130	−0.167	0.004	0.025
NF150	−0.236 *	0.044	0.055	−0.339 **	−0.062	−0.178	0.157	0.095	0.134
NF240	−0.357 *	0.120	0.134	−0.435 **	−0.126	−0.225 *	0.218 *	0.130	0.160
NF300	−0.278 *	0.133	0.147	−0.487 **	−0.120	−0.296 **	0.281 **	0.151	0.170

Note: The change of soil surface moisture was denoted at 10 cm below the soil surface under N application and 20 cm below the soil surface under no N application. NF0: N fertilization rate of 0 kg/ha; NF150: N fertilization rate of 150 kg/ha; NF240: N fertilization rate of 240 kg/ha; NF300: N fertilization rate of 300 kg/ha. * represents significant difference at $p < 0.05$ level. ** represents significant difference at $p < 0.01$ level.

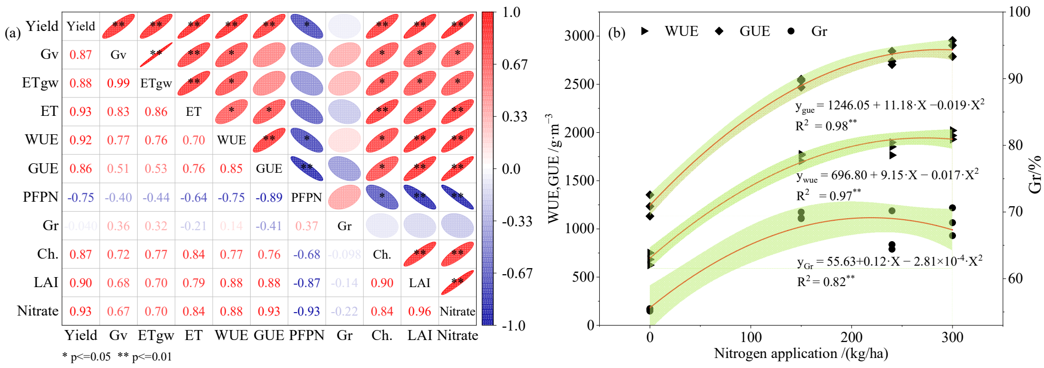

Figure 9. Correlation analysis of winter wheat grain yield, crop growth attributes, water use, PFPN, and nitrate accumulation in the vadose zone (**a**); Fitting relationship between GUE, WUE, and Grand N application rate (**b**). PFPN: Partial factor productivity of applied N, Ch.: crop height of winter wheat.

4. Discussion

During the whole growth stage of the winter wheat, the crop evapotranspiration was increased due to the enhanced root water absorption capacity after the regreening stage, and atmospheric evaporation was strengthened by the rising air temperature. The increase of crop transpiration and the atmospheric evaporation resulted in the groundwater evaporation enhancement of winter wheat, which reached the maximum in the filling stage [37,38]. In our study, 0.6 m groundwater depth was controlled by Lysimeters, and Gv in each N application treatment had a short-term peak at the regreening stage, which may be caused by short-term temperature rising (Figures 1 and 5a). Gv increased significantly at the late jointing stage, reached the maximum at the filling stage, and then decreased (Figures 5 and 7a), which was similar to the previous research [37,38]. The variation of Gv in the 150–300 kg/ha N application treatment was larger than that in the no N application treatment during the whole growth period (Figure 5a,b). Irrigation and precipitation would interfere with Gv, and Gv significantly decreased after irrigation under all N application treatments (Figure 5a). This is mainly due to irrigation increasing the upper soil moisture, the water potential gradient with the lower soil being decreased, and the short-term groundwater evaporation intensity being decreased. However, the degree of interference was limited by the amount of irrigation or precipitation and external meteorological conditions [39].

In terms of Gv intensity, Babajimopoulos et al. [4] found that that the Gv of summer maize was 3.6 $mm \cdot d^{-1}$ when the groundwater depth was about 0.6 m; Liu et al. [40] showed that Gv of winter wheat was 3.71–3.79 $mm \cdot d^{-1}$ under 0.7 m depth, and the maximum Gv was nearly 8 $mm \cdot d^{-1}$. In our study, the Gv of winter wheat was 1.57–3.40 $mm \cdot d^{-1}$ under N application, slightly lower than Babajimopoulos et al. [4] and Liu et al. [40]. This is mainly because the temperature can promote groundwater evaporation (Table 3), and the temperature during the growth period of winter wheat was lower than that of summer maize, and the irrigation amount in our study was relatively higher, which reduced the Gv (Figure 5a). In addition, the Gv, ETgw, and ET of winter wheat increased with the increase of N application, in particular, these parameters were significantly higher under N treatments than these under the no N treatment (Figures 5 and 7), and the maximum Gv was 7.14 $mm \cdot d^{-1}$ under 300 kg/ha application (Figure 5), indicating that the increase of the N application had a significant promoting effect on groundwater evaporation. The ETgw, ET, WUE, and grain yield were subsequently increased (Figure 9). The N application's addition may increase the solute potential gradient in the vadose zone and the water potential gradient in the upper and lower layers (Figure 4), increasing groundwater consumption [41]; on the other hand, shallow groundwater may have negative effects on the growth of winter wheat (Figure 3), such as waterlogging damage, and the high groundwater table may easily form a reducing environment, leading to nitrogen loss [42–44]. Increased N application can alleviate the adverse effects of a high groundwater table such as waterlogging to a certain extent, increasing the water use, crop growth attributes and grain yield (Figure 9a) [45,46]. This may be the main reason that adding the N application promoted the groundwater consumption and winter wheat yield (Figures 4 and 7).

Under the N application, the Gv of winter wheat showed a significant negative correlation with surface soil moisture, air relative humidity, and atmospheric pressure, especially at the heading to the maturity stage, Gv continued to strengthen (Table 3, Figure 5a), and surface soil moisture significantly decreased (Figure 6a); Gv was positive with atmospheric temperature significantly, similar to previous research [47–49]. Moreover, the correlation between Gv and meteorological factors gradually strengthened with the increase in N application rate in our study (Table 3), which may be due to the fact that increased N application under a high water table promoted crop growth and increased the water carrying capacity of soil interspaces [37], and shallow groundwater was more sensitive to environmental and meteorological conditions.

Shallow groundwater is an important source of crop water consumption and a major component of crop water demand, significantly affecting crop water productivity. Previous studies have shown that the ET of crops was 499.33–660 mm under a groundwater depth of 0.5–1.5 m with 100–500 mm irrigation, WUE was 0.85–1.87 $kg \cdot m^{-3}$, and crop (winter wheat) groundwater utilization rate (Gr) was 29–90% [13–16,34,47,50,51]. In our study, these indices were similar to those obtained in previous studies [13–16,34,47,50,51]. In addition, these indices were significantly affected by N application. Grain yield, crop growth attributes, ET, GUE, and WUE without N application were lower and they increased with the increasing N application rate (Figures 3, 4, 7 and 8); grain yield was positive with Gv, ETgw, ET, growth attributes, WUE, and GUE significantly (Figure 9a). These results indicated that N application at the shallow groundwater depth could promote the absorption and utilization of groundwater by crops and the improving of crop growth attributes, then increasing yield and WUE [7,52]. This may be similar to

Harries et al.'s [29] research that N application can promote crop water use and increase the yield under surface irrigation. Furthermore, Soylu et al. [53] showed that the 0.8–1.0 m depth was the critical depth for groundwater to produce anaerobic stress, so the growth of winter wheat may be inhibited [54,55]. In our study, under 0.6 m depth, the yield, WUE, and GUE of winter wheat with 0–150 kg/ha N application were low, but the yield and water use were significantly improved when the N application rate exceeded 150 kg/ha, indicating that adding N application could boost the resistance of winter wheat to the adverse environment of the high water table and increase water use and yield. This may be due to the balance of water and nitrogen in a crop-soil system under a high N application rate and high water table, which promoted crop growth, and the high N fertilization could provide more nitrogen to compensate for the N lost by denitrification under the high water table [44]. But the higher N application rate was not the better one; the higher N application rate will increase the nitrate content in the vadose zone [31,56]. In our study, from the N fertilization of 150–300 kg/ha, the nitrate accumulation in the vadose zone increased by 8.12 times sharply while the yield increased by 24.19%. The accumulation rate of nitrate was obviously higher than the yield increase rate when N was more than 150 kg/ha (Figure 4), which indicated that 150 kg/ha N application was a key N application rate at 0.6 m depth. There would be potential risks such as groundwater nitrate pollution and increased greenhouse gas emissions in the atmosphere, and this would also significantly reduce the partial factor productivity of the applied N under high N application [8,30,57]. Therefore, through a fitting analysis of GUE, WUE, and Gr with N application rate (Figure 9b), it can be found that 219.42–289.53 kg/ha was an optimal N application rate under 0.6 m groundwater depth with the condition of relatively strong alkaline soil. Moreover, in order to obtain the optimal N application rate and the optimal groundwater depth, the combined effects of different groundwater depths and different N application rates on crop yield, groundwater, and nitrogen use need to be studied further.

5. Conclusions

Under shallow groundwater depth, the increasing N application rate significantly increased the sensitivity of the daily groundwater evaporation velocity of winter wheat to environmental meteorological factors and promoted crop water use, crop growth and yield. From 150 kg/ha to 300 kg/ha N fertilization, LAI and yield increased by 26.95–82.02%, and water use increased by 11.17–14.38%.

N application had a significant effect on water transfer and could promote the consumption and utilization of groundwater at 0.6 m depth. But a high N application rate would induce surface soil drought, leading to a rapid increase in nitrate accumulation in the vadose zone and a significant decrease in partial factor productivity of applied N. With the N application of 150–300 kg/ha, the accumulation of nitrate in the vadose zone increased by 8.12 times, and soil moisture in 0–20 cm and partial factor productivity of applied N significantly decreased by 19.16–57.53%. Considering the groundwater utilization rate, groundwater and water use efficiency of crops, and nitrate accumulation in the vadose zone, the optimal N application rate was 219.42–289.53 kg/ha under the groundwater depth of 0.6 m. Nitrogen application at shallow groundwater depths significantly affected winter wheat growth, yield, water and nitrogen use, but the combined effects of different groundwater depths and different nitrogen application rates on yield, water and nitrogen use and the microbial mechanism of winter wheat yield affected by nitrogen application and groundwater depth need to be studied further.

Author Contributions: Conceptualization, Y.S. and X.Q.; methodology, Y.S. and W.G.; software, Y.S. and P.L.; validation, W.G. and Z.D.; investigation, Y.S., S.Z. and T.L.; resources, X.Q.; data curation, Y.S.; writing—original draft preparation, Y.S.; writing—review and editing, X.Q. and W.G.; visualization, Y.S.; supervision, X.Q. and W.G.; project administration, X.Q., P.L. and Z.D.;

funding acquisition, X.Q. All authors have read and agreed to the published version of the manuscript.

Funding: We are grateful for National Key R&D Program of China (No. 2021YFD1700900), Central Public-interest Scientific Institution Basal Research Fund (No. FIRI20210105 and No. CAAS-ZDRW202201), the National Natural Science Foundation of China (No. 51679241, 51709265), Central Public-interest Scientific Institution Basal Research Fund (Y2022GH10), and the Agricultural Science and Technology Innovation Program of Chinese Academy of Agricultural Sciences (No. CAAS-ASTIP).

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The data presented in this study are available within the article.

Acknowledgments: We would like to thank Xinxiang Muye District Xianyure Agriculture, Forestry and Water Science and Technology Service Center and Shandong Renke Measurement and Control Technology Co., LTD for the support to our experiment.

Conflicts of Interest: The authors declare that they have no conflicts of interest.

References

1. Lian, J.; Li, Y.; Li, Y.; Zhao, X.; Zhang, T.; Wang, X.; Wang, X.; Wang, L.; Zhang, R. Effect of Center-Pivot Irrigation Intensity on Groundwater Level Dynamics in the Agro-Pastoral Ecotone of Northern China. *Front. Environ. Sci.* **2022**, *10*, 892577. https://doi.org/10.3389/fenvs.2022.892577.
2. Russo, T.A.; Lall, U. Depletion and response of deep groundwater to climate-induced pumping variability. *Nat. Geosci*. **2017**, *10*, 105–108. https://doi.org/10.1038/ngeo2883.
3. Dai, J.; Li, R.; Miao, Q.; Li, C.; Lu, Y.; Hua, Z. Shallow groundwater enhances water productivity of maize in arid area. *Irrig. Sci.* **2022**, *40*, 885–908. https://doi.org/10.1007/s00271-022-00800-3.
4. Babajimopoulos, C.; Panoras, A.; Georgoussis, H.; Arampatzis, G.; Hatzigiannakis, E.; Papamichail, D. Contribution to irrigation from shallow water table under field conditions. *Agric. Water Manag*. **2007**, *92*, 205–210. https://doi.org/10.1016/j.agwat.2007.05.009.
5. Liu, H.; Wang, Z.; Yu, R.; Li, F.; Li, K.; Cao, H.; Yang, N.; Li, M.; Dai, J.; Zan, Y.; et al. Optimal nitrogen input for higher efficiency and lower environmental impacts of winter wheat production in China. *Agric. Ecosyst. Environ*. **2016**, *224*, 22. https://doi.org/10.1016/j.agee.2016.03.022.
6. Rasmussen, I.S.; Dresbøll, D.B.; Thorup-Kristensen, K. Winter wheat cultivars and nitrogen (N) fertilization—Effects on root growth, N uptake efficiency and N use efficiency. *Eur. J. Agron.* **2015**, *68*, 38–49. https://doi.org/10.1016/j.eja.2015.04.003.
7. Cossani, C.M.; Slafer, G.A.; Savin, R. Nitrogen and water use efficiencies of wheat and barley under a Mediterranean environment in Catalonia. *Field Crops Res.* **2012**, *128*, 109–118. https://doi.org/10.1016/j.fcr.2012.01.001.
8. Yu, C.; Huang, X.; Chen, H.; Godfray, H.C.J.; Wright, J.S.; Hall, J.W.; Gong, P.; Ni, S.; Qiao, S.; Huang, G.; et al. Managing nitrogen to restore water quality in China. *Nature* **2019**, *567*, 516–520. https://doi.org/10.1038/s41586-019-1001-1.
9. Si, Z.; Zain, M.; Mehmood, F.; Wang, G.; Gao, Y.; Duan, A. Effects of nitrogen application rate and irrigation regime on growth, yield, and water-nitrogen use efficiency of drip-irrigated winter wheat in the North China Plain. *Agric. Water Manag.* **2020**, *231*, 106002. https://doi.org/10.1016/j.agwat.2020.106002.
10. Ruiz, A.; Salvagiotti, F.; Gambin, B.L.; Borrás, L. Maize nitrogen management in soils with influencing water tables within optimum depth. *Crop Sci*. **2021**, *61*, 1386–1399. https://doi.org/10.1002/csc2.20379.
11. Liu, L.; Luo, Y.; Lai, J.; Liu, T. Study on extinction depth and steady water storage in root zone based on lysimeter experiment and HYDRUS-1D simulation. *Hydrol. Res.* **2015**, *46*, 871–879. https://doi.org/10.2166/nh.2015.191.
12. Yang, J.; Wan, S.; Deng, W.; Zhang, G. Water fluxes at a fluctuating water table and groundwater contributions to wheat water use in the lower Yellow River flood plain, China. *Hydrol. Process*. **2007**, *21*, 717–724. https://doi.org/10.1002/hyp.6246.
13. Kahlown, M.A.; Ashraf, M.; Ziaul, H. Effect of shallow groundwater table on crop water requirements and crop yields. *Agric. Water Manag*. **2005**, *76*, 24–35. https://doi.org/10.1016/j.agwat.2005.01.005.
14. Fidantemiz, Y.F.; Jia, X.; Daigh, A.L.M.; Hatterman-Valenti, H.; Steele, D.D.; Niaghi, A.R.; Simsek, H. Effect of Water Table Depth on Soybean Water Use, Growth, and Yield Parameters. *Water* **2019**, *11*, 931. https://doi.org/10.3390/w11050931.
15. Gao, X.; Huo, Z.; Xu, X.; Qu, Z.; Huang, G.; Tang, P.; Bai, Y. Shallow groundwater plays an important role in enhancing irrigation water productivity in an arid area: The perspective from a regional agricultural hydrology simulation. *Agric. Water Manag.* **2018**, *208*, 43–58. https://doi.org/10.1016/j.agwat.2018.06.009.
16. Huo, Z.; Feng, S.; Huang, G.; Zheng, Y.; Wang, Y.; Guo, P. Effect of Groundwater Level Depth and Irrigation Amount on Water Fluxes at the Groundwater Table and Water Use of Wheat. *Irrig. Drain*. **2012**, *61*, 348–356. https://doi.org/10.1002/ird.685.
17. Ren, F.; Sun, N.; Xu, M.; Zhang, X.; Wu, L.; Xu, M. Changes in soil microbial biomass with manure application in cropping systems: A meta-analysis. *Soil. Till. Res*. **2019**, *194*, 104291. https://doi.org/10.1016/j.still.2019.06.008.

18. Qiu, S.; Gao, H.; Zhu, P.; Hou, Y.; Zhao, S.; Rong, X.; Zhang, Y.; He, P.; Christie, P.; Zhou, W. Changes in soil carbon and nitrogen pools in a Mollisol after long-term fallow or application of chemical fertilizers, straw or manures. *Soil. Till. Res*. **2016**, *163*, 255–265. https://doi.org/10.1016/j.still.2016.07.002.
19. Wu, X.; Cai, X.; Li, Q.; Ren, B.; Bi, Y.; Zhang, J.; Wang, D. Effects of nitrogen application rate on summer maize (*Zea mays* L.) yield and water–nitrogen use efficiency under micro–sprinkling irrigation in the Huang–Huai–Hai Plain of China. *Arch. Agron. Soil Sci*. **2021**, *68*, 1915–1929. https://doi.org/10.1080/03650340.2021.1939867.
20. Treseder, K.K. Nitrogen additions and microbial biomass: A meta-analysis of ecosystem studies. *Ecol. Lett*. **2008**, *11*, 1111–1120. https://doi.org/10.1111/j.1461-0248.2008.01230.x.
21. He, W.; Jiang, R.; He, P.; Yang, J.; Zhou, W.; Ma, J.; Liu, Y. Estimating soil nitrogen balance at regional scale in China's croplands from 1984 to 2014. *Agric. Syst*. **2018**, *167*, 125–135. https://doi.org/10.1016/j.agsy.2018.09.002.
22. Zhang, Y.; Wang, H.; Lei, Q.; Zhang, J.; Zhai, L.; Ren, T.; Liu, H. Recommended methods for optimal nitrogen application rate. *Sci. Agric. Sin.* **2018**, *51*, 2937–2947. (In Chinese with English Abstract)
23. Yan, M.; Luo, T.; Bian, R.; Cheng, K.; Pan, G.; Rees, R. A comparative study on carbon footprint of rice production between household and aggregated farms from Jiangxi, China. *Environ. Monit. Assess*. **2015**, *187*, 332. https://doi.org/10.1007/s10661-015-4572-9.
24. Zhou, J.; Ma, Y.; Wu, M.; Peng, Z.; Wang, Y.; Li, H.; Wang, Y.; Sheng, L. Water and Nitrogen Utilization and Biological Effects of Winter Wheat under Different Water and Fertilizer Measures. *J. Irrig. Drain*. **2019**, *38*, 36–41. https://doi.org/10.13522/j.cnki.ggps.2019074. (In Chinese with English Abstract)
25. Kumar, R.; Pareek, N.K.; Kumar, U.; Javed, T.; Al-Huqail, A.A.; Rathore, V.S.; Nangia, V.; Choudhary, A.; Nanda, G.; Ali, H.M.; et al. Coupling Effects of Nitrogen and Irrigation Levels on Growth Attributes, Nitrogen Use Efficiency, and Economics of Cotton. *Front. Plant Sci.* **2022**, *13*, 890181. https://doi.org/10.3389/fpls.2022.890181.
26. Ji, Y.; Feng, W.; Hao, X.; Peng, Y.; Han, P.; Ma, Z.; Zhang, L. Effects of Different Fertilization Pattern on the Yield of the Rotation System of Wheat and Maize and Soil Nitrate Accumulation in North China Plain. *Ecol. Environ. Sci.* **2014**, *11*, 1725–1731. https://doi.org/10.16258/j.cnki.1674-5906.2014.11.018. (In Chinese with English Abstract)
27. Sun, M.; Huo, Z.; Zheng, Y.; Dai, X.; Feng, S.; Mao, X. Quantifying long-term responses of crop yield and nitrate leaching in an intensive farmland using agro-eco-environmental model. *Sci. Total Environ.* **2018**, *613–614*, 1003–1012. https://doi.org/10.1016/j.scitotenv.2017.09.080.
28. Naghdyzadegan Jahromi, M.; Razzaghi, F.; Zand-Parsa, S. Strategies to increase barley production and water use efficiency by combining deficit irrigation and nitrogen fertilizer. *Irrig. Sci*. **2022**, *2022*, 1–15. https://doi.org/10.1007/s00271-022-00811-0.
29. Harries, M.; Flower, K.C.; Renton, M.; Anderson, G.C.; Sadras, V. Water use efficiency in Western Australian cropping systems. *Crop Pasture Sci.* **2022**, *73*, 1097–1117. https://doi.org/10.1071/cp21745.
30. Cui, Z.; Zhang, H.; Chen, X.; Zhang, C.; Ma, W.; Huang, C.; Zhang, W.; Mi, G.; Miao, Y.; Li, X.; et al. Pursuing sustainable productivity with millions of smallholder farmers. *Nature* **2018**, *555*, 363–366. https://doi.org/10.1038/nature25785.
31. Zhou, J.; Gu, B.; Schlesinger, W.H.; Ju, X. Significant accumulation of nitrate in Chinese semi-humid croplands. *Sci. Rep.* **2016**, *6*, 25088. https://doi.org/10.1038/srep25088.
32. Yang, X.; Lu, Y.; Ding, Y.; Yin, X.; Raza, S.; Tong, Y. a. Optimising nitrogen fertilisation: A key to improving nitrogen-use efficiency and minimising nitrate leaching losses in an intensive wheat/maize rotation (2008–2014). *Field Crops Res.* **2017**, *206*, 16. https://doi.org/10.1016/j.fcr.2017.02.016.
33. Kadioglu, H.; Hatterman-Valenti, H.; Jia, X.; Chu, X.; Aslan, H.; Simsek, H. Groundwater Table Effects on the Yield, Growth, and Water Use of Canola (*Brassica napus* L.) Plant. *Water* **2019**, *11*, 1730. https://doi.org/10.3390/w11081730.
34. Liu, Z.; Niu, H.; Jia, Y. Influence of Groundwater Depth on Evapotranspiration of Winter Wheat. *Water Sav. Irrig.* **2010**, *2020*, 1–3. (In Chinese with English Abstract)
35. Cassman, K.G.; Peng, S.; Olk, D.C.; Ladha, J.K.; Reichardt, W.; Dobermann, A.; Singh, U. Opportunities for Increased Nitrogen–Use Efficiency from Improved Resource Management in Irrigated Rice Systems. *Field Crops Res*. **1998**, *56*, 7–39.
36. Idowu, O.; Wang, Y.; Homma, K.; Nakazaki, T.; Xu, Z.; Shiraiwa, T. Interaction of erect panicle genotype and nitrogen fertilizer application on the source-sink ratio and nitrogen use efficiency in rice. *Field Crops Res.* **2022**, *278*, 108430. https://doi.org/10.1016/j.fcr.2022.108430.
37. Li, R.; Wang, Y.; Liu, M.; Chen, X. Research on Relation Between Crop Growth and Shallow Groundwater in North of Anhui Province. *Water Sav. Irrig*. **2013**, *2013*, 30–41. (In Chinese with English Abstract)
38. Zhang, X.; Wang, Z.; Du, F.; Wang, B.; Li, R.; Lu, L. Study on the Relationship Between Soil Water and Groundwater Conversion in Wheat Field and Bare Land in Lime Concretion Black Soil. *Water Sav. Irrig*. **2020**, *2020*, 57–60. (in Chinese with English Abstract).
39. Barbeta, A.; Penuelas, J. Relative contribution of groundwater to plant transpiration estimated with stable isotopes. *Sci. Rep*. **2017**, *7*, 10580. https://doi.org/10.1038/s41598-017-09643-x.
40. Liu, T.; Liu, L.; Luo, Y.; Lai, J. Simulation of groundwater evaporation and groundwater depth using SWAT in the irrigation district with shallow water table. *Environ. Earth Sci.* **2015**, *74*, 315–324. https://doi.org/10.1007/s12665-015-4034-2.
41. Müller, L.; Augustin, J.; Eulenstein, F.; Seeger, J.; Meissner, R.; Behrendt, A.; Schindler, U. Einfluss unterschiedlicher böden auf die ausnutzung von wasser und stickstoff durch weidelgras, sommergerste und mais auf einigen grundwasserstandorten. *Arch. Agron. Soil Sci.* **2001**, *47*, 277–292. https://doi.org/10.1080/03650340109366215.

42. Ma, S.; Wang, Y.; Huang, Z.; Han, X.; Zhang, W.; Fan, Y.; Ma, Y. Research Progress of Effects of Waterlogging on Wheat Growth and Cultivation Technique for Waterlogging Resistance. *J. Triticeae Crops* **2019**, *39*, 835–843. https://doi.org/10.7606/j.issn.1009-1041.2019.07.11. (In Chinese with English Abstract)
43. Herzog, M.; Striker, G.G.; Colmer, T.D.; Pedersen, O. Mechanisms of waterlogging tolerance in wheat--a review of root and shoot physiology. *Plant Cell Environ.* **2016**, *39*, 1068–1086. https://doi.org/10.1111/pce.12676.
44. Li, Z.; Zhang, Q.; Qiao, Y.; Leng, P.; Zhang, Q.; Du, K.; Tian, C.; Li, X.; Chen, G.; Li, F. Influence of the shallow groundwater table on the groundwater N2O and direct N2O emissions in summer maize field in the North China Plain. *Sci. Total Environ*. **2021**, *799*, 149495. https://doi.org/10.1016/j.scitotenv.2021.149495.
45. Mueller, L.; Behrendt, A.; Schalitz, G.; Schindler, U. Above ground biomass and water use efficiency of crops at shallow water tables in a temperate climate. *Agric. Water Manag*. **2005**, *75*, 117–136. https://doi.org/10.1016/j.agwat.2004.12.006.
46. Ogola, J.B.O.; Wheeler, T.R.; Harris., P.M. Effects of nitrogen and irrigation on water use of maize crops. *Field Crops Res*. **2005**, *78*, 105–117.
47. Gu, N.; Zhang, J.; Liu, C.; Wang, Z.; Wang, G. An experimental study of the influence of groundwater level on water consumption of winter wheat in the Huaibei Plain. *Hydrogeol. Eng. Geol.* **2021**, *48*, 15–24. https://doi.org/10.16030/j.cnki.issn.1000-3665.202011053. (In Chinese with English Abstract)
48. Lu, X.; Yang, M.; Wang, Z.; Lyu, H.; Gu, N. Metrological Factors Affecting Evaporation of Shallow Groundwater in the Absence of Plants in Huaibei Plain. *J. Irrig. Drain*. **2019**, *38*, 84–91. https://doi.org/10.13522/j.cnki.ggps.20180459. (In Chinese with English Abstract)
49. Wang, Z.; Liu, M.; Li, R. Experiment on phreatic evaporation of bare soil and soil with crop in Huaibei plain. *Trans. CSAE* **2009**, *25*, 26–32. https://doi.org/10.3969/j.issn.1002-6819.2009.06.005. (In Chinese with English Abstract)
50. Huang, J.; Zhou, Y.; Wenninger, J.; Ma, H.; Zhang, J.; Zhang, D. How water use of Salix psammophila bush depends on groundwater depth in a semi-desert area. *Environ. Earth Sci.* **2016**, *75*, 556. https://doi.org/10.1007/s12665-016-5376-0.
51. Karimov, A.K.; Šimůnek, J.; Hanjra, M.A.; Avliyakulov, M.; Forkutsa, I. Effects of the shallow water table on water use of winter wheat and ecosystem health: Implications for unlocking the potential of groundwater in the Fergana Valley (Central Asia). *Agric. Water Manag*. **2014**, *131*, 57–69. https://doi.org/10.1016/j.agwat.2013.09.010.
52. Liu, W.; Wang, J.; Wang, C.; Ma, G.; Wei, Q.; Lu, H.; Xie, Y.; Ma, D.; Kang, G. Root Growth, Water and Nitrogen Use Efficiencies in Winter Wheat Under Different Irrigation and Nitrogen Regimes in North China Plain. *Front Plant Sci*. **2018**, *9*, 1798. https://doi.org/10.3389/fpls.2018.01798.
53. Soylu, M.E.; Kucharik, C.J.; Loheide, S.P. Influence of groundwater on plant water use and productivity: Development of an integrated ecosystem—Variably saturated soil water flow model. *Agric. Forest Meteorol.* **2014**, *189–190*, 198–210. https://doi.org/10.1016/j.agrformet.2014.01.019.
54. Deng, C.; Zhang, Y.; Bailey, R.T. Evaluating crop-soil-water dynamics in waterlogged areas using a coupled groundwater-agronomic model. *Environ. Modell Softw*. **2021**, *143*, 105130. https://doi.org/10.1016/j.envsoft.2021.105130.
55. Gou, Q.; Zhu, Y.; Horton, R.; Lü, H.; Wang, Z.; Su, J.; Cui, C.; Zhang, H.; Wang, X.; Zheng, J.; et al. Effect of climate change on the contribution of groundwater to the root zone of winter wheat in the Huaibei Plain of China. Agric. *Water Manag.* **2020**, *240*, 106292. https://doi.org/10.1016/j.agwat.2020.106292.
56. Xin, J.; Liu, Y.; Chen, F.; Duan, Y.; Wei, G.; Zheng, X.; Li, M. The missing nitrogen pieces: A critical review on the distribution, transformation, and budget of nitrogen in the vadose zone-groundwater system. *Water Res.* **2019**, *165*, 114977. https://doi.org/10.1016/j.watres.2019.114977.
57. Guo, J.H.; Liu, X.J.; Zhang, Y.; Shen, J.L.; Han, W.X.; Zhang, W.F.; Christie, P.; Goulding, K.W.T.; Vitousek, P.M.; Zhang, F.S. Significant Acidification in Major Chinese Croplands. *Science* **2010**, *327*, 1008–1010. https://doi.org/10.1126/science.1182570.