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Groundwater Depth and Nitrogen Application Amount Jointly Regulate the Water and Residual Soil Nitrate Accumulation in Agricultural Soil Profile

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Abstract: Despite the known influence of groundwater conditions and nitrogen application on crop growth and the soil microenvironment, less information is available on the influence of groundwater depth and nitrogen application amount on the movement and accumulation of soil water and residual nitrate in deep soil in summer maize–winter wheat rotation systems. Therefore, a large lysimeter experiment was conducted to examine how groundwater depth and nitrogen application amount influence the transport and accumulation of soil water and nitrate in the summer maize (*Zea mays* L.)–winter wheat (*Triticum aestivum* L.) rotation system. The results showed that nitrogen reduction increased soil water storage both in the summer maize and winter wheat fields. The residual soil nitrate accumulation in the entire soil profile of summer maize and winter wheat under deeper groundwater depth treatment was higher than that of shallow groundwater depth treatment. Hence, the deeper the groundwater depth, the longer the nitrate transport path, and the nitrate that would have entered the groundwater accumulates in deep soil. The residual soil nitrate accumulation in the whole soil profile of winter wheat was 76.05–130.11 kg ha^{-1} higher than that of summer maize. Structural equation models (SEMs) showed that the nitrogen application amount not only exhibited a directly positive effect on the residual soil nitrate accumulation but also indirectly influenced it by regulating total soil nitrogen; groundwater depth only exhibited a directly negative effect on residual soil nitrate accumulation; and soil depth had an indirect positive effect on residual soil nitrate accumulation through the regulation of soil water storage. Together, our findings prove that groundwater depth and nitrogen application amount jointly regulate the residual soil nitrate accumulation in agricultural soil rotated with winter wheat and summer maize. Therefore, in formulating a fertilization strategy for regional agricultural green development, it is necessary to consider the fertilizer application amount rate and the groundwater depth.

Keywords: residual soil nitrate accumulation; groundwater depth; nitrogen application amount; soil water storage; summer maize and winter wheat rotation

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1. Introduction

The North China Region is an important food production base in China. The planting area of winter wheat and summer maize in the North China Region accounts for 72.3% and 31.3% of the whole country, respectively, and the output of winter wheat and summer maize accounts for 79.8% and 30.1% of the total national output, respectively [1]. Nitrogen is essential for plant growth and crop production [2]. However, excessive fertilization is often used to increase crop yields [3]. A large amount of nitrogen application in agriculture greatly reduces the utilization efficiency [4,5]. The surpassed nitrogen entering the environment leads to groundwater nitrate pollution [6] and the aggravation of greenhouse gas emissions [7]. Chronic exposure to high levels of nitrate through drinking water and dermal contact increases the risk of cancer in humans [8], and the increased greenhouse gas emissions will cause global warming which will lead to a series of climate disasters [9]. The large application of nitrogen fertilizer is one of the important causes of nitrate pollution in groundwater [10]. The vadose zone connects the surface and groundwater; it acts as a buffer and filter zone and is the last gateway for nitrate leaching into groundwater [11]. Accordingly, improving knowledge of the transport and transformation of nitrate nitrogen in the soil profile can help us better understand the fate of nitrate.

When all kinds of common nitrogen fertilizer are applied or microorganisms mineralize organic fertilizer, it is mainly absorbed in the form of NH_4^+ and kept in the soil layer. After being absorbed by crops and partially volatilized, the remaining part migrates to the deep soil layer in the form of NO_3^--N and NO_2^--N under the nitrification of soil microorganisms [12]. Nitrate is highly soluble and is easily lost by leaching as water moves below the root zone of the soil profile [13]. The vadose zone above groundwater is an important barrier to preventing nitrogen pollution of groundwater. Denitrification can effectively prevent and eliminate nitrate due to leaching [14]. The downward transport of nitrate in the soil profile lags behind the downward transport of soil water, and the storage and transport of soil water drive the migration and accumulation of nitrate in the soil [15]. Therefore, the vadose zone can reduce the risk of groundwater nitrate pollution mainly through the blocking and dissipating effects of migration nitrogen.

Nitrogen application amount is the key factor affecting nitrogen leaching [16]. The distribution of nitrate in deep soil increases with the increase in nitrogen application amount but decreases with the increase in soil depth. Soil nitrate content in the 20~200 cm soil layer has been found to be significantly affected by organic carbon and dissolved organic nitrogen in the soil profile [17]. The potential risk of N leaching increases with the increase in residual N in soil [18]. High nitrogen application amounts usually result in a large nitrate load in the soil profile and a potential risk of groundwater contamination due to nitrate leaching. Therefore, a proper nitrogen application amount and reasonable irrigation can improve crop yield and the recovery rate of nitrogen fertilizer, minimize environmental damage, and save water resources and production costs [19]. When the nitrogen application amount increases from 0 to 320 kg N ha^{-1}, the leaching loss of nitrate increases from 14.6 kg N ha^{-1} to 250 kg N ha^{-1} [20]. Therefore, reducing the nitrogen application amount is an effective method to reduce nitrate leaching. Nitrogen application can directly affect water and nitrogen transport by regulating soil nitrate concentration and can also indirectly affect nitrogen absorption and transport by regulating crop growth and soil properties. Accordingly, it is necessary to study the specific path of nitrogen application amount on soil water and nitrogen transport.

Groundwater depth affects the soil profile microenvironment, nitrogen conversion microbial diversity, and denitrification intensity and has important effects on the crop. The deeper the shallow groundwater depth, the lower the salt content of the surface soil [21]; surface soil salinity increases with the increase in groundwater salinity [22]. With the increase in groundwater depth, the capillary water in soil decreases, so the accumulation of salt in the soil profile decreases [23]. The groundwater depth determines the boundary of saturated and unsaturated soil zones and affects the depth of the soil's aerobic/anaerobic boundary and REDOX state [24]. At the same time, groundwater depth also affects soil pH, soil organic matter content, and soil enzyme activity, which is the catalyst of the nitrogen conversion process [25]. Groundwater depth and nitrogen application regulate the community composition of denitrifying bacteria, which are one important part of the nutrient cycle and directly determine the biogeochemical process of soil N [26]. Other studies have shown that the abundance of denitrifying genes gradually increase with the increase in the groundwater table and the duration of flooding [27]. At the same time, groundwater depth affects crop growth and water use efficiency [28,29]. Soil denitrification is closely related to nitrate transport, so any soil environmental factors that affect denitrification potential may also affect soil water and nitrate nitrogen transport. However, the influence path of groundwater depth on soil water and nitrate transport is not clear.

Our world is facing severe global climate change, extreme hydrological events occur frequently, and aquifer water levels change dramatically; the excessive application of chemical fertilizers in agriculture causes a series of ecological and environmental problems, such as agricultural non-point source pollution and groundwater environment deterioration. Meeting the challenges of climate change and human activities and ensuring the safety of food and the ecological environment deserve wide attention from scientists worldwide. The effects of groundwater depth and nitrogen application amount on soil water and nitrogen transport must be explored. Therefore, based on a large long-term monitoring infiltration lysimeter platform, a winter wheat–summer maize rotation experiment was carried out with groundwater depth and nitrogen application amount as experimental factors. In this study, we aimed (1) to ascertain the effects of groundwater depth and nitrogen application amount on soil water characteristics and residual soil nitrate as well as their accumulation in soil profile; (2) to reveal the direct and indirect effects of groundwater depth and nitrogen application amount, soil depth, and other soil factors (soil water storage and soil total nitrogen) on residual soil nitrate accumulation according to structural equation models (SEMs); (3) to clarify the coupled relationship between soil nitrate and water in deep soil in the North China Region.

2. Materials and Methods

2.1. Study Site Description

The experiment was conducted in the long-term monitoring lysimeter (Figure 1) located at the Xinxiang Agricultural Water and Soil Environment Field Scientific Observation and Experiment Station, Chinese Academy of Agricultural Sciences (35°19′ N, 113°53′ E), Xinxiang City, Henan Province, People's Republic of China. The planting pattern is winter wheat–summer maize rotation with two crops a year. Two experimental factors, groundwater depth and nitrogen application amount, were used in the present experiment due to their consistency for a long period. The topographical parameters of the study area were split into an annual average temperature of 14.1 °C, an annual average frost-free period of about 210 d, an annual average sunshine duration of 2398.8 h, and an annual average rainfall of 588.8 mm. The annual variation in precipitation is large; the precipitation difference between wet years and dry years is 3~4 times; precipitation from July to September accounts for about 70% of the annual precipitation; and the annual average evaporation is approximately 2000 mm. The test soil is silty loam, and the main physical and chemical properties are shown in Table 1. The maximum depths of the lysimeter are 2.8 m, 4.8 m, and 5.3 m; the area of the lysimeter is 1.5×3 m^2; and each lysimeter is a reinforced concrete structure with a bottom (Figure 2).

Figure 1. Field experiment of long-term monitoring lysimeter in Xinxiang Agricultural Water and Soil Environment Field Scientific Observation and Experiment Station, Chinese Academy of Agricultural Sciences.

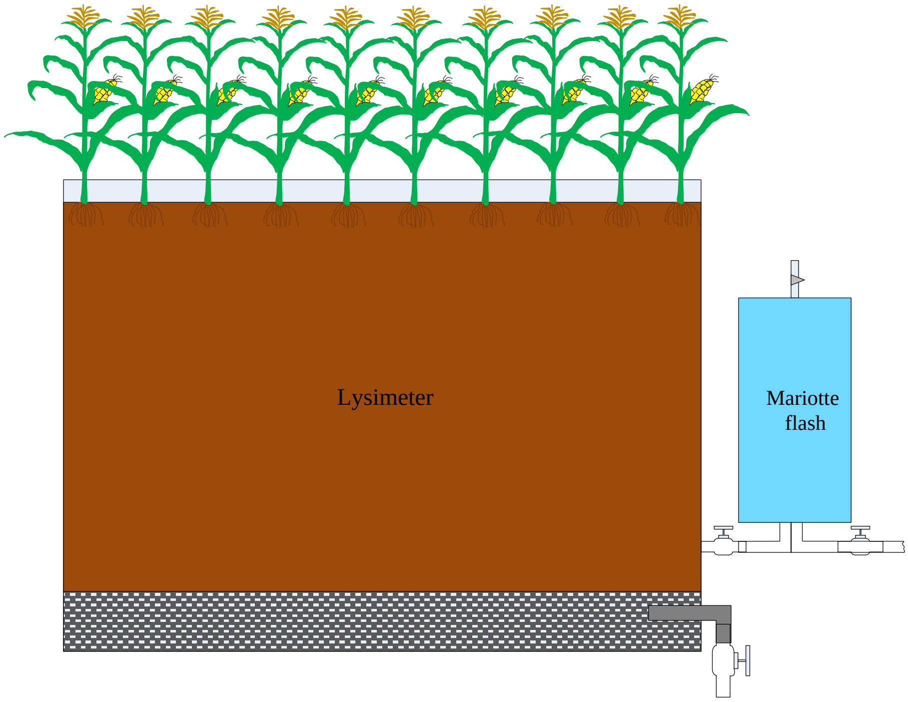

Figure 2. Lysimeter schematic plot.

Table 1. Physical and chemical properties of test soil.

Soil Depth/cm	Soil Mechanical Composition/%			Soil Bulk Density/ ($g\ cm^{-3}$)	Field Water Holding Capacity/%	Wilting Moisture Content/%	Organic Matter/ ($g\ kg^{-1}$)	Total Nitrogen/ ($g\ kg^{-1}$)	Total Phosphorus/ ($g\ kg^{-1}$)	Available Potassium/ ($g\ kg^{-1}$)	*EC*/ ($\mu S\ cm^{-1}$)	pH
	<0.002 mm	0.002~0.02 mm	0.02~2.0 mm									
0~20	6.85	52.61	40.54	1.40	22.39	9.38	14.30	0.32	0.66	0.19	568.90	9.13
20~40	7.49	53.47	39.04	1.41	22.05	9.11	13.64	0.28	0.56	0.15	679.70	9.06

2.2. Experimental Layout

The experimental summer maize (*Zea Mays* L.) was Huaiyu 208, which was sown on 10 June 2020 and harvested on 23 September 2020. The whole growth period was 105 days, and the planting density was 66,699 plants ha^{-1}. The experimental winter wheat (*Triticum aestivum* L.) variety was Bainong 4199, which was sown on 20 October 2020 and harvested on 28 May 2021 with a sowing rate of 165 kg ha^{-1}. The experiment set groundwater depth and nitrogen application amount as two factors. Groundwater depth was set at three levels, which were 2 m (GW2), 3 m (GW3), and 4 m (GW4). The nitrogen application amount was set at two levels: the farmers' conventional nitrogen application amount (pure nitrogen 300 kg ha^{-1}, N300) and 20% nitrogen reduction (pure nitrogen 240 kg ha^{-1}, N240). There were 6 treatments in total, which were referred to as N240GW2, N240GW3, N240GW4, N300GW2, N300GW3, and N300GW4. Each treatment had 4 replicates, so there was a total of 24 plots with an area of 1.5 $\times$ 3 m^2 (Figure 1 for details). The experimental field was surrounded with protective strips as buffer zones to minimize edge effects. A RS-XAJ-100 probe produced by Jinan Renshuo Electronic Technology Co., Ltd. (Jinan, China) was buried in the 20 cm soil layer to monitor soil water and temperature. Irrigation was carried out in combination with the 20 cm soil layer's soil water content, the plot's situation, the plot's actual situation, and the crops' water shortage (Figure 3). Well water was used for irrigation, and the irrigation method was ground irrigation. Calcium superphosphate (12%, P_2O_5, 150 kg ha^{-1}) and potassium sulfate (K_2O, 50%, 120 kg ha^{-1}) were applied once in each crop season before plowing (0–20 cm), and urea (N, 46.3%) was split into two applications. Basal N fertilization accounted for 40% of the total application amount for summer maize, and 60% for winter wheat. The basic fertilizer was applied when maize was sown, and the top-dressing fertilizer was applied in the big trumpet stage. The basic fertilizer was applied at the sowing time of winter wheat, and the top-dressing fertilizer was applied at the regreening–jointing stage. Other field management measures were the same as in the local field.

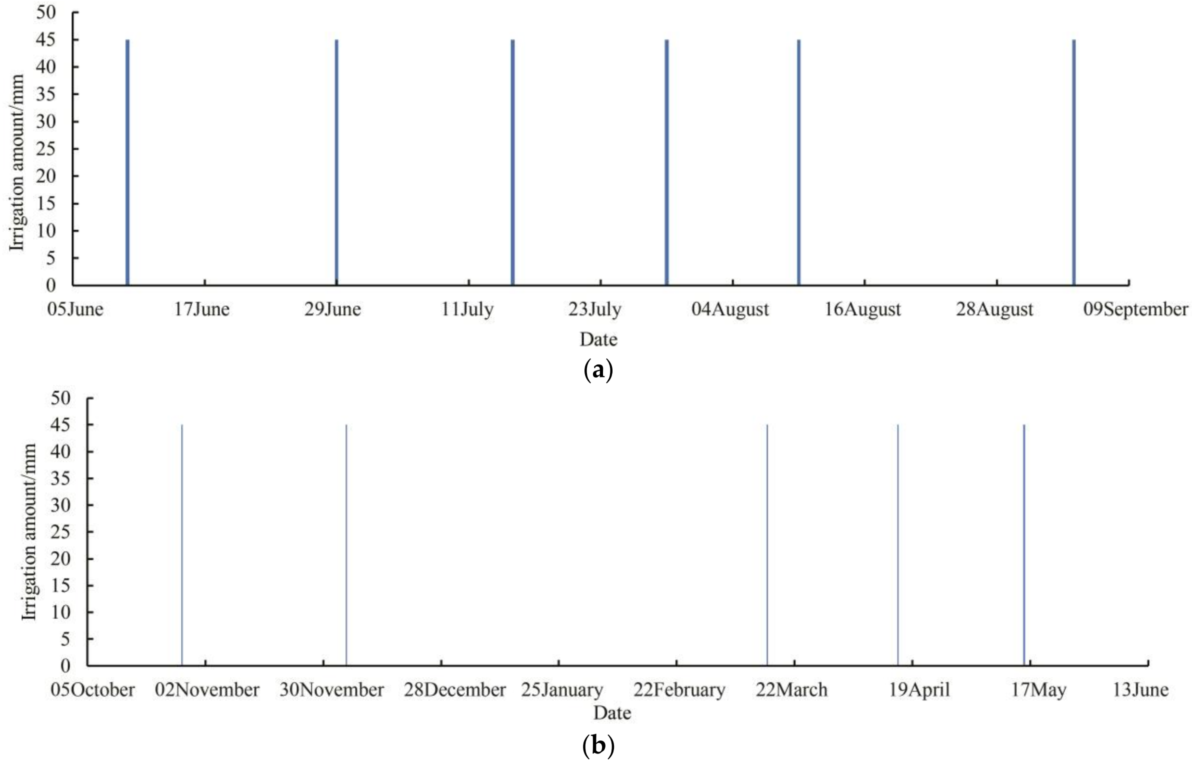

Figure 3. Irrigation amount for the whole growth period of crops. (**a**) Summer maize; (**b**) Winter wheat.

2.3. Sampling and Statistical Analysis

2.3.1. Soil Sampling and Experimental Method

We randomly collected 3 cores of soil samples in each plot using an auger to constitute a composite sample from each soil layer after the summer maize and winter wheat harvest in 2020–2021. Every 20 cm is 1 layer, and the soil sampling depths of the GW2, GW3, and GW4 treatments are 2 m, 3 m, and 4 m, respectively. One part of the fresh soil was put into an aluminum box, and the soil water content was determined by the drying method. The other part of the fresh soil was sealed immediately in plastic bags and taken to the laboratory to determine the soil nitrate content. The determination method was to take 10 g of fresh soil in a triangular flask, extract it with 50 mL 0.01 mol L^{-1} $CaCl_2$ solution, shake it for 30 min, and then use a flow Analyzer (Bran Luebbe AA3) for determination [30]. The remaining soil samples were air-dried and stored at room temperature to study the soil's total nitrogen (TN), total phosphorus (TP), pH, EC, and soil organic matter.

2.3.2. Calculation of Soil Water Storage in Soil Profiles

The soil water storage (*SWS*, mm) was calculated using the following formula [15]:

$$SWS = (W_i \times T_i \times D_i)/10,$$

where W_i is the soil mass water content (%), T_i is the soil layer thickness (cm), D_i is the soil bulk density (g cm^{-3}), 1/10 is the conversion coefficient, and *i* is the soil layer. Since the soil water content and nitrate nitrogen in the 0–60 cm layer vary greatly, and the lower soil is relatively stable, soil layer depths are re-divided when calculating soil water storage. Hence, *i* are 0–20 cm, 20–40 cm, 40–60 cm, 60–100 cm, 100–200 cm, 200–300 cm, and 300–400 cm; the soil bulk density of 0–20 cm, 20–40 cm, 40–60 cm, 60–100 cm, 100–120 cm, 120–140 cm, 140–160 cm, and the soil layer below 180 cm are 1.4 g cm^{-3}, 1.41 g cm^{-3}, 1.42 g cm^{-3}, 1.42 g cm^{-3}, 1.43 g cm^{-3}, 1.435 g cm^{-3}, 1.44 g cm^{-3}, and 1.45 g cm^{-3}, respectively.

2.3.3. Calculation of Nitrate Accumulation in Soil Profiles

The soil nitrate accumulation (SNA, kg ha^{-1}) in each soil layer was calculated using the following equation [15,31]:

$$SNA = (T_i \times D_i \times C_i)/10,$$

where C_i (mg kg^{-1}) is the soil nitrate content in the corresponding soil layer, T_i is the soil layer thickness (cm), D_i is the soil bulk density (g cm^{-3}), 1/10 is the conversion coefficient, and i is the soil layer, i.e., 0–20 cm, 20–40 cm, 40–60 cm, 60–100 cm, 100–200 cm, 200–300 cm, and 300–400 cm.

2.3.4. Structural Equation Modeling

Structural equation modeling (SEM) was used to tease apart the causal pathways through which groundwater depth and nitrogen application amount influence residual soil nitrate accumulation [15]. Before analysis, prior structural equation models were established which included three hierarchical pathways: (a) the direct effects of groundwater depth and nitrogen application amount on soil nitrate accumulation; (b) the indirect effects of groundwater depth and nitrogen application amount on soil nitrate accumulation through changes in soil properties; and (c) the indirect effects of groundwater depth and nitrogen application amount on soil properties through changes in soil nitrate. To simplify the model, soil water storage and soil TN were used because they highly affected soil nitrate, as determined using Spearman's correlation analysis. Hence, we selected soil water storage and total N in our SEM model.

2.4. Statistical Analysis

The data were analyzed by one-way analyses of variance (ANOVA) and two-way ANOVA using SPSS Statistics 17.0 (IBM Company, Armonk, NY, USA) to analyze whether significant differences existed among groundwater depths, nitrogen application amounts, and their interactions. The significance level used for all statistical tests was $p < 0.05$. SEM was performed using Amos 17.0 (IBM SPSS, Chicago, IL, USA). To ensure the data met the assumptions of normality in the model, the groundwater depth, nitrogen application amount, soil depth, soil water storage, and soil TN were subjected to standardized transformation. The overall SEM model was fitted using the following indexes [32]: comparative fit index (*CFI*), the goodness of fit index (*GFI*), low root square mean error of approximation (*RMSEA*), the p value of Fisher's C statistic, and the χ^2 statistic.

3. Results

3.1. Effects of Groundwater Depth and Nitrogen Application Amount on the Soil Water Content and Soil Water Storage at Different Soil Depth

The soil water content in the 0–20 cm soil layer was the lowest during the summer maize season. With the increase in soil depth, the soil water content of all treatments showed an overall increasing trend (Figure 4a–c). Compared with the N300 treatment, the N240 treatment had higher soil water content in all soil layers under GW2, GW3, and GW4 groundwater depths. Therefore, the N300 treatments reduced soil water storage at the maturity stage of summer maize. When averaged, the soil water content of the two nitrogen application amounts across 0–200 cm soil layers was as follows: GW2 > GW3 > GW4, and the differences among them were significant ($p < 0.05$); The soil water content of GW2, GW3, and GW4 treatments under the N240 application amounts was 4.18%, 11.29%, and 6.30% higher than that of the N300 application amount, respectively.

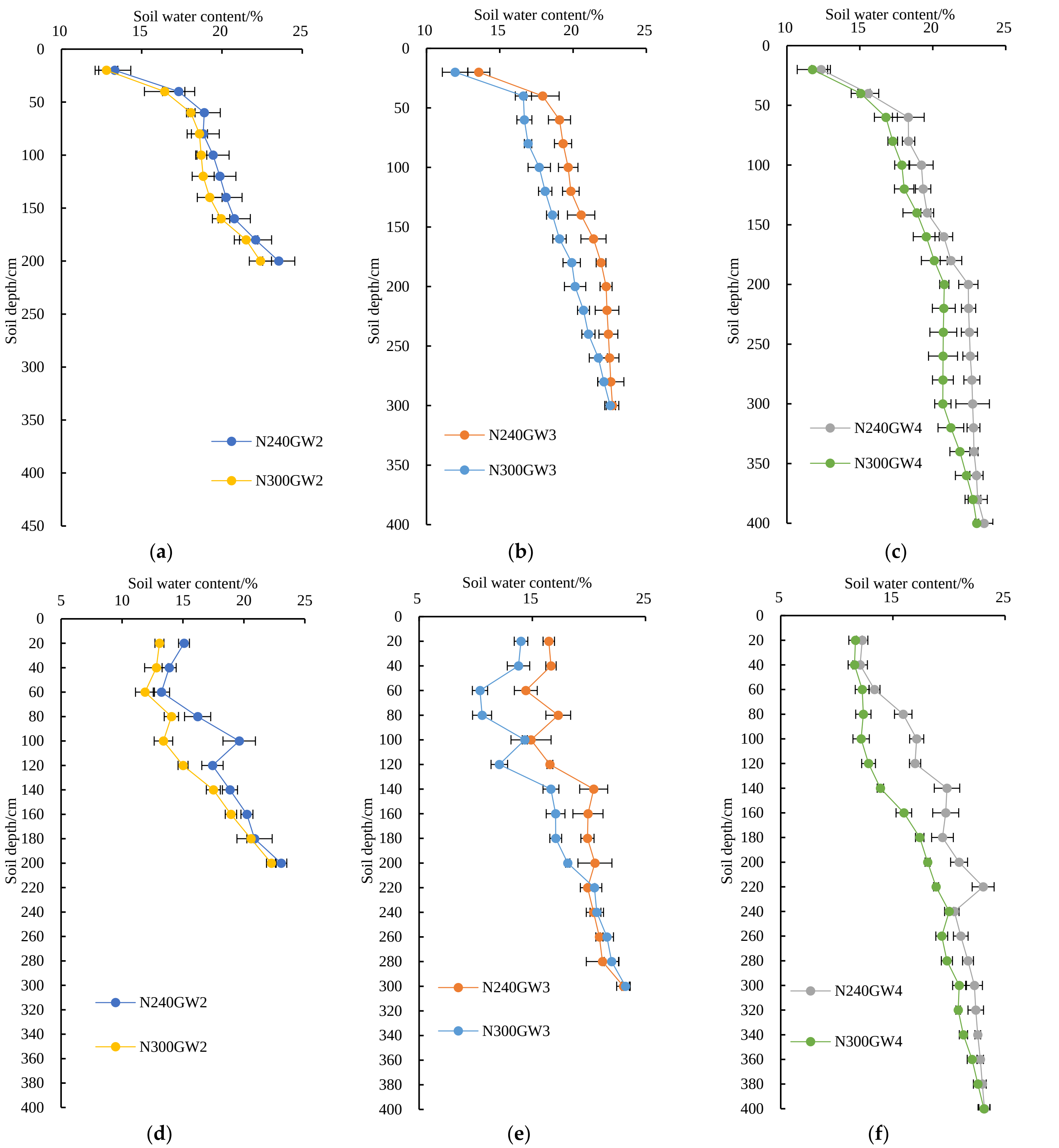

Figure 4. Soil water content of different soil depths at the maturity stage of summer maize and winter wheat. (**a**) GW2 in summer maize; (**b**) GW3 in summer maize; (**c**) GW4 in summer maize; (**d**) GW2 in winter wheat; (**e**) GW3 in winter wheat; (**f**) GW4 in winter wheat.

With the increase in soil depth, the soil water content of all treatments showed an overall increasing trend in the winter wheat season, except for some soil layers (Figure 4d–f). When the groundwater depth was 2 and 4 m, the soil water content in each soil layer of N240 treatments was higher than that of N300 treatments; when the groundwater depth was 3 m, the soil water content of N240 treatments was higher than the N300 treatment in the soil layer above 2 m, and it was lower than the N300 treatments in the

200–300 cm soil layer. When averaged the soil water content across the 0–200 cm soil layer, the soil water content under the N240 and N300 application amounts were both as follows: GW2 > GW3 > GW4; the soil water content of the GW2, GW3, and GW4 treatments under the N240 application amounts was 11.89%, 22.87%, and 21.23% higher than that of the N300 treatment, respectively. The soil water content in the 0–60 cm soil layer varies greatly, and the lower part is relatively stable (Figure 4). According to soil water content and nitrate content, the soil layer was divided into 0–20 cm, 20–40 cm, 40–60 cm, 60–100 cm, 100–200 cm, 200–300 cm, and 300–400 cm to analyze soil water storage and residual soil nitrate accumulation. In the 180–200 cm soil layer, the soil water content of the GW2 treatment was significantly higher than that of the GW3 and GW4 treatments under two nitrogen application amounts for summer maize and winter wheat.

With the increase in soil depth, the proportion of soil water storage in each soil layer increased gradually at the maturity stage of summer maize (Table 2). With the increase in groundwater depth, the proportion of soil water storage in each soil layer decreased gradually. The soil water storage in each soil layer of the GW2, GW3, and GW4 treatments under the N240 application amount was higher than that under the N300 application amount. The soil water storage of the entire soil profile of the GW2, GW3, and GW4 treatments under the N240 application amounts was 4.18%, 8.50%, and 6.27% higher than those under the N300 application amount, respectively. Under the N300 application amount, the soil water storage of the 0–60 cm soil layer under the GW2, GW3, and GW4 treatments was 133.45, 127.68, and 123.02 mm, respectively; meanwhile, they were 139.73, 142.71, and 130.52 mm under the N240 application amount, respectively. Therefore, the variation trend of soil water storage of the 0–60 cm soil layer with groundwater depth was inconsistent under different nitrogen application amounts, mainly because soil water storage was not only related to groundwater, but also related to crop transpiration and inter-tree evaporation. Under the N300 application amount, the soil water storage in the soil layer below 60 cm under the GW2, GW3, and GW4 treatments were 399.69, 688.07, and 1003.21 mm; meanwhile, they were 415.72, 742.34, and 1 066.31 mm under the N240 application amount, respectively. The increase in soil water storage due to nitrogen reduction in the soil layer below 60 cm accounted for 71.86%, 78.31%, and 89.38% of the total increase, so the soil water storage increased by N240 mainly concentrated in the soil layer below 60 cm.

With the increase in groundwater depth, the soil water storage in each soil layer at the maturity stage of winter wheat gradually decreased (Table 3). The soil water storage in the entire soil profile of the GW2, GW3, and GW4 treatments under the N240 application amounts were 8.94%, 5.38%, and 6.40% higher than those under the N300 application amounts, respectively. Under the N240 application amount, the soil water storage of the 0–60 cm soil layer under the GW2, GW3, and GW4 treatments was 118.93, 134.00, and 106.32 mm, respectively; they were 107.20, 113.23, and 101.53 mm under the N300 application amount, respectively. With the N240 application amount, the soil water storage in the soil layer below 60 mm under the GW2, GW3, and GW4 treatments were 391.37, 679.88, and 1017.98 mm, respectively; meanwhile, they were 361.22, 659.10, and 955.13 mm under the N300 application amount, respectively. The increased soil water storage in the soil layer below 60 cm accounted for 72.00%, 50.01%, and 92.92% of the total increase, so the increased soil water storage due to nitrogen reduction mainly concentrated in the soil layer below 60 cm.

Table 2. Soil water storage in each soil layer in summer maize.

Treatments		0~20 cm		20~40 cm		40~60 cm		60~100 cm		100~200 cm		200~300 cm		300~400 cm	
		Water Storage/mm	Proportion/%	Water Storage/mm	Proportion/%	Water Storage/mm	Proportion/%	Water Storage/mm	Proportion/%	Water Storage/mm	Proportion/%	Water Storage/mm	Proportion/%	Water Storage/mm	Proportion/%
	N240GW2	37.29 ± 4.24 a	6.71	48.78 ± 1.40 a	8.78	53.66 ± 1.45 a	9.66	108.68 ± 2.67 ab	19.57	307.04 ± 4.22 a	55.28				
	N240GW3	37.98 ± 2.12 a	4.29	50.56 ± 3.16 a	5.71	54.17 ± 2.14 a	6.12	110.71 ± 2.89 a	12.51	305.43 ± 6.44 b	34.51	326.20 ± 6.09 a	36.86		
	N240GW4	34.55 ± 1.79 a	2.89	43.93 ± 2.02 b	3.67	52.03 ± 3.09 a	4.35	106.66 ± 2.62 ab	8.91	298.07 ± 7.47 ab	24.90	327.50 ± 3.91 a	27.36	326.20 ± 2.28 a	27.91
	N300GW2	35.85 ± 1.98 a	6.72	46.33 ± 3.55 ab	8.69	51.28 ± 0.76 a	9.62	105.93 ± 0.97 b	19.87	293.76 ± 2.50 c	55.10				
	N300GW3	33.47 ± 2.44 a	4.10	46.85 ± 1.56 ab	5.74	47.36 ± 1.45 b	5.81	98.33 ± 2.20 c	12.05	276.19 ± 3.08 d	33.86	313.55 ± 5.00 b	38.44		
	N300GW4	32.90 ± 2.91 a	2.92	42.46 ± 1.83 b	3.77	47.66 ± 2.24 b	4.23	99.77 ± 1.97 c	8.86	280.74 ± 7.20 d	24.93	300.32 ± 7.03 c	26.67	322.39 ± 3.05 a	28.63
	N	3.94		5.10 *		23.02 **		45.55 **		58.84 **		37.56 **			
F	GW	1.75		8.49 **		2.66		4.93 *		7.06 **		3.37			
	N × GW	0.60		0.33		1.85		6.58 **		3.39		5.01 *			

Note: Different lowercase letters in the same column indicate significant differences among treatments at the $p < 0.05$ level; The * after the values in the table indicates significant differences between treatments at the $p < 0.05$ level, and ** indicates very significant differences at the $p < 0.01$ level, the same below.

Table 3. Soil water storage in each soil layer in winter wheat.

Treatments		0~20 cm		20~40 cm		40~60 cm		60~100 cm		100~200 cm		200~300 cm		300~400 cm	
		Water Storage/mm	Proportion/%	Water Storage/mm	Proportion/%	Water Storage/mm	Proportion/%	Water Storage/mm	Proportion/%	Water Storage/mm	Proportion/%	Water Storage/mm	Proportion/%	Water Storage/mm	Proportion/%
	N240GW2	42.24 ± 1.25 b	8.28	39.10 ± 1.63 b	7.66	37.58 ± 1.90 ab	7.36	101.73 ± 5.72 a	19.93	289.65 ± 4.91 a	56.76				
	N240GW3	46.07 ± 1.42 a	5.68	46.95 ± 1.29 a	5.78	40.97 ± 2.87 a	5.05	91.39 ± 7.98 b	11.26	280.48 ± 7.19 b	34.55	305.86 ± 7.83 a	37.68		
	N240GW4	34.33 ± 1.41 de	3.05	34.06 ± 1.83 c	3.03	37.93 ± 1.40 ab	3.37	93.83 ± 3.99 b	8.35	279.12 ± 7.03 b	24.83	314.76 ± 1.52 a	28.00	330.26 ± 2.29 a	29.38
	N300GW2	36.60 ± 1.03 d	8.02	36.15 ± 2.72 bc	7.92	33.75 ± 2.21 c	7.40	77.96 ± 2.98 c	17.08	271.89 ± 2.30 b	59.58				
	N300GW3	39.21 ± 1.67 c	5.41	38.86 ± 2.79 b	5.36	29.48 ± 1.91 d	4.07	70.72 ± 2.21 cd	9.75	233.55 ± 6.10 c	32.21	313.24 ± 6.10 a	43.20		
	N300GW4	32.65 ± 1.66 e	3.26	32.65 ± 1.61 c	3.26	34.83 ± 1.76 bc	3.48	69.67 ± 0.66 d	6.96	225.46 ± 1.22 c	22.53	286.91 ± 1.71 b	28.67	318.56 ± 3.52 a	31.83
	N	49.61 **		18.31 **		40.08 **		111.58 **		248.22 **		12.11 **		-	
F	GW	63.63 **		32.41 **		0.481		6.785 **		49.52 **		8.79 *			
	N × GW	5.43 *		4.34 *		7.65 **		0.26		19.36 **		35.88 **		-	

Note: Different lowercase letters in the same column indicate significant differences among treatments at the $p < 0.05$ level; The * after the values in the table indicates significant differences between treatments at the $p < 0.05$ level, and ** indicates very significant differences at the $p < 0.01$ level, the same below.

3.2. Effects of Groundwater Depth and Nitrogen Application Amount on the Soil Nitrate Content and Residual Nitrate Content at Different Soil Depths

The soil nitrate content in the summer maize and winter wheat fields was affected directly by the groundwater depth and the nitrogen application amount (Figure 5). When averaged across all soil depths under two nitrogen application amounts, the soil nitrate content of the GW4 treatment (21.19 mg kg^{-1}) was significantly lower than that of the GW2 and GW3 treatments (24.61 and 24.99 mg kg^{-1}) in the summer maize fields ($p < 0.05$), but there was no significant difference between the GW2 and GW3 treatments. However, the averaged soil nitrate content in the soil profile of GW2, GW3, and GW4 treatments in winter wheat fields were 27.94, 27.65, and 23.22 mg kg^{-1}, respectively; there was a significant difference between the GW4, GW2, and GW3 treatments ($p < 0.05$), but no significant difference between the GW2 and GW3 treatments.

Under the same nitrogen application amount, soil nitrate content at the soil–water interface of summer maize and winter wheat decreased with the increase in groundwater depth. Under the N240 treatment, soil nitrate contents at the soil–water interface of the GW2, GW3, and GW4 treatments of summer maize were 39.15, 27.94, and 21.39 mg kg^{-1}, respectively, and the differences among the three groundwater depth treatments were significant ($p < 0.05$). Under the N300 application amount, the three treatments were 64.69, 42.32, and 33.78 mg kg^{-1}, respectively, and the differences among the three treatments were also extremely significant ($p < 0.05$). Under the N240 application amount, the soil nitrate content at the soil–water interface of the GW2 treatment (35.83 mg kg^{-1}) was significantly higher than that of GW3 and GW4 treatments (13.92 and 12.49 mg kg^{-1}) in the winter wheat fields ($p < 0.05$); meanwhile, it was 40.78, 35.19, and 31.86 mg kg^{-1} for the GW2, GW3, and GW4 treatments under the N300 application amount, and there was a significant difference only between GW2 and GW4 ($p < 0.05$).

In the 180–200 cm soil layer, soil nitrate content of the GW2 treatment (39.15 mg kg^{-1}) was significantly higher than that of the GW3 and GW4 treatments (25.35 and 20.23 mg kg^{-1}) under the N240 application amounts for summer maize ($p < 0.05$); while the soil nitrate content in the 180–200 cm soil layer of the GW2, GW3, and GW4 treatments under the N300 application amount for summer maize were 64.69, 36.45, and 23.59 mg kg^{-1}, respectively, and the differences among the three treatments were significant ($p < 0.05$). The soil nitrate contents in the 180–200 cm soil layer of GW2, GW3, and GW4 under the N300 application amount were 65.26%, 43.78%, and 16.60% higher than those under the N240 application amount for summer maize, respectively. In the 180–200 cm soil layer, the soil nitrate content of the GW2 treatment (35.83 mg kg^{-1}) was significantly higher than that of the GW3 and GW4 treatments (26.46 and 24.86 mg kg^{-1}) under the N240 application amount for winter wheat ($p < 0.05$). Soil nitrate content in the GW2 and GW3 treatments (40.78 and 33.24 mg kg^{-1}) was significantly higher than that of the GW4 treatment (23.69 mg kg^{-1}) under the N300 application amount ($p < 0.05$). Therefore, the shallower the groundwater is buried, the higher the nitrate pollution risk of groundwater. Nitrogen reduction is a direct way to reduce nitrate pollution in groundwater.

The residual soil nitrate accumulation in the summer maize and winter wheat fields was affected directly by the groundwater depths and the nitrogen application amounts (Tables 4 and 5). The N300 treatment increased the residual soil nitrate accumulation by 36.02% and 35.55% in the entire soil profile for summer maize and winter wheat, respectively. The residual soil nitrate accumulation in the entire soil profile of summer maize under the GW3 and GW4 treatments was 52.74% and 72.98% higher than that of the GW2 treatment, respectively, and the differences among them were significant ($p < 0.05$). The residual soil nitrate accumulation in the entire soil profile of winter wheat under the GW3 and GW4 treatments was 48.91% and 67.01% higher than those of GW2 treatment, respectively, and the differences among them were also extremely significant ($p < 0.05$).

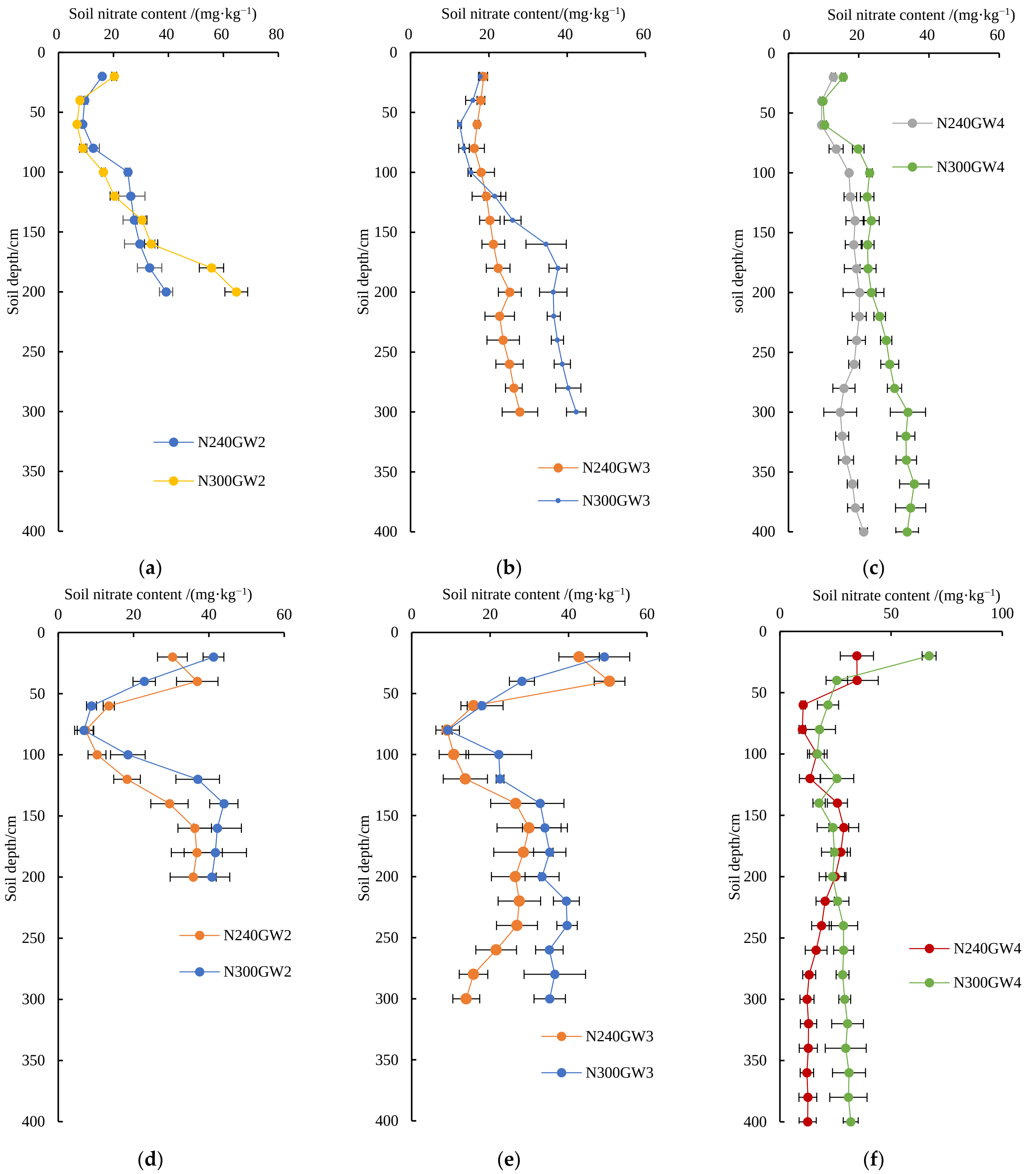

Figure 5. Soil nitrate content at different soil depths at the maturity stage of of summer maize and winter wheat. (**a**) GW2 in summer maize; (**b**) GW3 in summer maize; (**c**) GW4 in summer maize; (**d**) GW2 in winter wheat; (**e**) GW3 in winter wheat; (**f**) GW4 in winter wheat.

Table 4. Residual soil nitrate accumulation in each soil layer in summer maize.

	Treatments	0~20 cm		20~40 cm		40~60 cm		60~100 cm		100~200 cm		200~300 cm		300~400 cm	
		Accumulation/ (kg ha^{-1})	Proportion/%	Accumulation/ (kg ha^{-1})	Proportion/%	Accumulation/ (kg ha^{-1})	Proportion/%	Accumulation/ (kg ha^{-1})	Proportion/%	Accumulation/ (kg ha^{-1})	Proportion/%	Accumulation/ (kg ha^{-1})	Proportion/%	Accumulation/ (kg ha^{-1})	Proportion/%
	N240GW2	44.48 ± 1.06 c	6.81	26.77 ± 3.20 cd	4.10	24.96 ± 1.50 d	3.82	107.45 ± 7.59 b	16.46	449.09 ± 54.21 b	68.80				
	N240GW3	52.31 ± 2.76 b	5.64	50.69 ± 2.82 a	5.47	48.30 ± 1.56 a	5.21	97.54 ± 11.79 bc	10.52	312.91 ± 27.95 c	33.74	365.55 ± 27.36 c	39.42		
	N240GW4	35.78 ± 1.65 d	3.69	26.59 ± 1.30 cd	2.75	26.75 ± 0.82 d	2.76	87.52 ± 5.67 cd	9.03	273.02 ± 39.76 c	28.18	257.24 ± 13.05 d	26.55	261.91 ± 15.00 b	27.03
	N300GW2	56.77 ± 2.51 a	7.47	21.83 ± 1.08 d	2.87	19.02 ± 0.41 e	2.50	71.26 ± 2.07 e	9.37	591.46 ± 17.32 a	77.79				
	N300GW3	49.90 ± 1.31 b	4.05	44.91 ± 5.23 b	3.65	35.61 ± 1.31 b	2.89	82.59 ± 3.91 de	6.71	451.09 ± 17.38 b	36.64	566.88 ± 23.59 a	46.05		
	N300GW4	43.69 ± 1.58 c	2.96	27.64 ± 0.45 c	1.87	29.12 ± 1.62 c	1.97	121.98 ± 5.08 a	8.27	330.65 ± 28.93 c	22.41	425.67 ± 13.82 b	28.85	496.80 ± 13.10 a	33.67
	N	43.25 **		5.79 *		80.44 **		3.04		50.91 **		246.17 **			
F	GW	67.89 **		121.99 **		383.73 **		9.92 **		65.22 **		112.10 **			
	N × GW	23.35 **		2.57		51.95 **		43.12 **		3.50		1.95			

Note: Different lowercase letters in the same column indicate significant differences among treatments at the $p < 0.05$ level; The * after the values in the table indicates significant differences between treatments at the $p < 0.05$ level, and ** indicates very significant differences at the $p < 0.01$ level, the same below.

Table 5. Residual soil nitrate accumulation in each soil layer in winter wheat.

	Treatments	0~20 cm		20~40 cm		40~60 cm		60~100 cm		100~200 cm		200~300 cm		300~400 cm	
		Accumulation/ (kg ha^{-1})	Proportion/%	Accumulation/ (kg ha^{-1})	Proportion/%	Accumulation/ (kg ha^{-1})	Proportion/%	Accumulation/ (kg ha^{-1})	Proportion/%	Accumulation/ (kg ha^{-1})	Proportion/%	Accumulation/ (kg ha^{-1})	Proportion/%	Accumulation/ (kg ha^{-1})	Proportion/%
	N240GW2	84.88 ± 9.60 d	11.65	104.09 ± 13.43 b	14.28	38.08 ± 3.64 bc	5.23	49.77 ± 7.67 d	6.83	451.98 ± 30.21 b	62.02				
	N240GW3	119.54 ± 12.50 b	11.61	142.28 ± 9.55 a	13.82	44.91 ± 4.06 b	4.36	56.19 ± 12.13 cd	5.46	360.80 ± 38.03 c	35.04	306.03 ± 36.19 c	29.72		
	N240GW4	96.92 ± 18.08 cd	9.11	97.87 ± 23.21 bc	9.20	29.73 ± 2.47 c	2.79	75.80 ± 11.05 abc	7.13	347.19 ± 14.99 c	32.64	234.08 ± 11.27 d	22.00	182.24 ± 13.32 b	17.13
	N300GW2	115.41 ± 6.68 bc	13.27	64.36 ± 7.25 d	7.40	25.08 ± 3.23 c	2.88	71.84 ± 16.74 bcd	8.26	592.94 ± 23.94 a	68.18				
	N300GW3	137.54 ± 15.66 b	10.18	79.26 ± 7.78 cd	5.87	50.92 ± 13.20 ab	3.77	89.11 ± 19.64 ab	6.60	454.76 ± 33.38 b	33.67	538.93 ± 32.98 a	39.91		
	N300GW4	187.90 ± 7.60 a	11.70	72.17 ± 11.80 d	4.49	61.43 ± 11.69 a	3.83	98.39 ± 12.39 a	6.13	332.35 ± 22.92 c	20.70	407.51 ± 26.07 b	25.38	445.90 ± 67.23 a	27.77
	N	63.25 **		46.58 **		5.12 *		15.73 **		30.30 **		154.59 **		-	
F	GW	18.10 **		7.73 **		7.86 **		5.44 *		63.99 **		38.72 **			
	N × GW	14.85 **		3.01		12.68 **		0.29		11.94 **		3.31		-	

Note: Different lowercase letters in the same column indicate significant differences among treatments at the $p < 0.05$ level; The * after the values in the table indicates significant differences between treatments at the $p < 0.05$ level, and ** indicates very significant differences at the $p < 0.01$ level, the same below.

The residual soil nitrate accumulation in the entire soil profile of winter wheat was 76.05 kg ha^{-1}, 102.45 kg ha^{-1}, 95.02 kg ha^{-1}, 109.29 kg ha^{-1}, 119.52 kg ha^{-1}, and 130.11 kg ha^{-1} higher than that of summer maize under N240GW2, N240GW3, N240GW4, N300GW2, N300GW3, and N300GW4, and the increased nitrate was mainly concentrated in the 0–60 cm soil layer. The residual soil nitrate accumulation in the soil 100 cm above the groundwater depth of GW2, GW3, and GW4 for summer maize was 449.09, 365.55, and 261.91 under the N240 application amount, respectively; it was 591.46, 566.88, and 496.80 under the N300 application amount. The residual soil nitrate accumulation in the soil 100 cm above the groundwater table of GW2, GW3, and GW4 for winter wheat was 451.98, 306.03, and 182.24 under the N240 application amount, respectively; it was 592.94, 538.93, and 445.90 under the N300 application amount. Therefore, the high nitrogen application amount increased residual soil nitrate accumulation in the deep soil profile, and the deep groundwater treatment decreased the residual soil nitrate accumulation in the deep soil profile.

The residual soil nitrate accumulation of summer maize and winter wheat showed a trend of decreasing first and then increasing with the increase in soil depth in the entire soil profile. In the 100–200 cm soil layer, the residual soil nitrate accumulation of summer maize and winter wheat decreased with the increase in groundwater depth under the two nitrogen application amounts. The residual soil nitrate accumulation of the GW2 treatment was 36.20% and 72.37% higher than that of the GW3 and GW4 treatments for summer maize; there was a significant difference among them ($p < 0.05$). The residual soil nitrate accumulation of the GW2, GW3, and GW4 treatments under N300 was 31.70%, 44.16%, and 21.11% higher than that under N240 treatment of summer maize, respectively. The residual soil nitrate accumulation of the GW2 treatment was 28.12% and 53.77% higher than that of GW3 and GW4 treatments for winter wheat, respectively, and the difference among them was extremely significant ($p < 0.05$). The residual soil nitrate accumulation in the 100–200 cm soil layer of the GW2, GW3, and GW4 treatments under N300 was 31.19%, 26.04%, and −4.27% higher than that under the N240 treatment of winter wheat, respectively. The GW2 treatment increased the residual soil nitrate accumulation in the 100–200 cm soil layer and decreased the residual soil nitrate accumulation in the 0–100 cm soil layer (except N240GW4 of summer maize). Overall, the shallower the groundwater depth, the higher the risk of nitrate pollution in groundwater. The deeper the groundwater, the longer the migration path of soil nitrate nitrogen, and the lower the risk of groundwater nitrate pollution.

3.3. Effects of Groundwater Depth, Nitrogen Application Amount, Soil Depth, and Soil Factors on Residual Soil Nitrate Accumulation

We used the SEMs to tease apart the direct effects of groundwater depth and nitrogen application amount on residual soil nitrate accumulation as well as the indirect effects regulated by soil depth and soil factors. According to the SEM results, we found that the nitrogen application amount exhibited a consistent positive relationship with residual nitrate accumulation in the summer maize and winter wheat fields (Figure 6). The magnitude of the positive partial effect of nitrogen application amount on residual nitrate accumulation increased from the summer maize field (r = 0.408) to the winter wheat field (r = 0.482, $p < 0.01$, Figure 6). In addition, the effect of the nitrogen application amount on nitrate accumulation was regulated by soil total nitrogen, but the indirect effect of the nitrogen application amount on nitrate accumulation through soil total nitrogen was inconsistent in the summer maize and winter wheat fields, with $r = -0.092$ ($p < 0.01$) in the summer maize field and $r = 0.173$ ($p < 0.01$) in winter wheat field (Figure 6). There was a consistent negative correlation between groundwater depth and residual soil nitrate accumulation in the different soil layers of summer maize and winter wheat. The magnitude of the negative effect of groundwater depth on residual nitrate accumulation declined from the summer maize field ($r = -0.183$, $p < 0.01$) to the winter wheat field ($r = -0.109$, Figure 6). However, the groundwater depth in the summer maize field also indirectly affected residual soil nitrate accumulation by influencing soil water storage, and the standardized path coefficient of groundwater depth on soil water storage was −0.070 ($p < 0.05$).

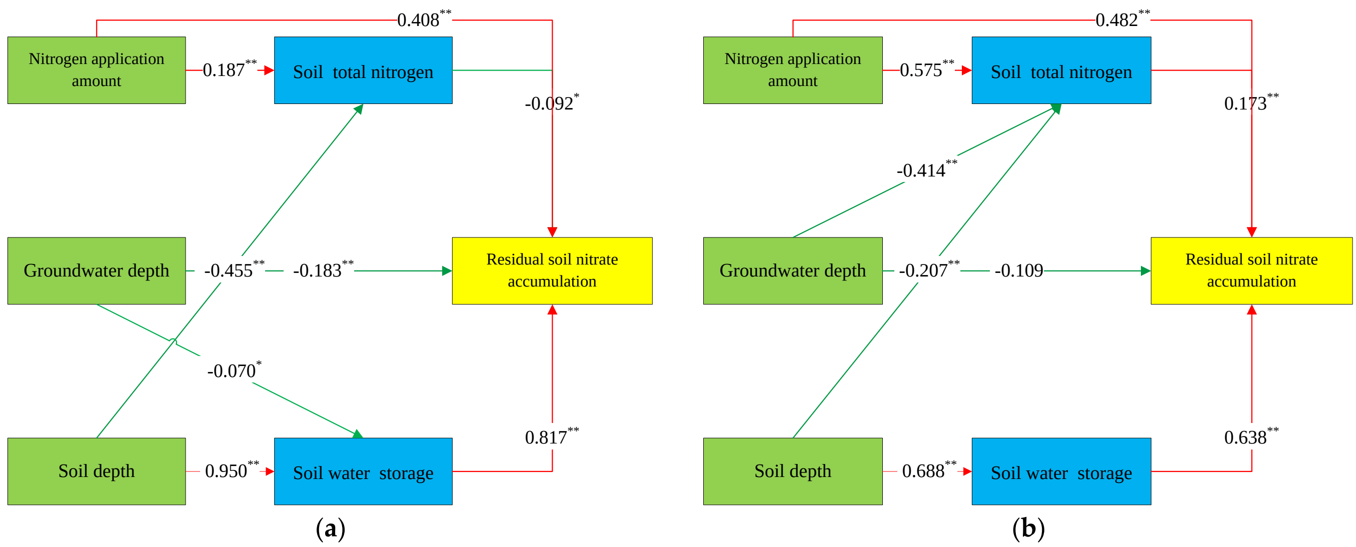

Figure 6. SEMs (structural equation models) fitted to connections among residual soil nitrate accumulation and the effects of groundwater depth, nitrogen application amount, and soil factors (soil depth, soil total nitrogen, soil water storage) in summer maize field (χ^2 = 14.217, *DF* = 10, *GFI* = 0.997, *CFI* = 0.995, *RMSEA* = 0.051, p = 0.163) and winter wheat field (χ^2 = 6.623, *DF* = 10, *GFI* = 0.990, *CFI* = 1.004, *RMSEA* = 0.000, p = 0.761). Numbers adjacent to arrows represent the standardized path coefficients(r) (** $p < 0.01$, * $p < 0.05$). (**a**) Summer maize; (**b**) Winter wheat.

Interestingly, the path analysis indicated that soil depth had an indirect positive effect on residual soil nitrate accumulation in the summer maize and winter wheat fields (Figure 6). The path coefficient of indirect effects declined from the summer maize field (r = 0.950) to the winter wheat field (r = 0.688, $p < 0.01$, Figure 6). The indirect effects of soil depth on residual soil nitrate accumulation were regulated by soil water storage. The strongest positive effect regulated by soil water storage was r = 0.817 ($p < 0.01$) in the summer maize field and r = 0.638 ($p < 0.01$) in winter wheat field.

4. Discussion

4.1. Soil Water Characteristics Affected by Groundwater Depth, Nitrogen Application Amount

It is widely believed that groundwater depth and nitrogen application amount influence soil water conditions and crop water use efficiency [18,33,34]. Our results showed that compared with the N240 application amount, the N300 application amount led to a certain degree of decline in the soil water storage of the soil profile at maturity. Consequently, soil water storage decreased with the increase in nitrogen application amount at maturity. This is mainly because the high nitrogen application amount increases the crop's water consumption, leading to a decrease in soil water storage [35]. We also found that the mean soil water content of 0–200 cm was in the order of GW2 > GW3 > GW4. The groundwater contribution decreases when the groundwater table is lowered [23], and the exchange between soil water and groundwater will decrease with the increase in groundwater depth. Therefore, suitable groundwater depth can improve crop irrigation water use efficiency and increase capillary rise [36]. In our study, the increased soil water storage due to nitrogen reduction mainly concentrated in the soil layer below 60 cm, which was likely related to the crop root length density and distribution. A stable isotope study showed that the main water uptake soil layer for summer maize was 0–20 cm at the trefoil stage (77.8%), the mature stage (35.0%), and the harvest stage (52.4%). Th main water uptake soil layer for winter wheat was also concentrated within 0–20 cm. The proportion of water absorption in the 0–20 cm soil layer ranged from 86.6% at the wintering to 67.8% at the mature stage [37].

This is a good explanation for the fact that the soil layer below 60 cm is less affected by crops. More importantly, we found that the variation trend of soil water storage in the 0–60 cm soil layer with groundwater depth was inconsistent under different nitrogen application amounts. This was mainly because soil water storage was not only related to groundwater but also to crop evapotranspiration and soil evaporation. Moreover, soil evaporation accounted for 29.7% and 30.3% of the total evapotranspiration for winter wheat and summer maize, respectively [38]. The proportion of soil evaporation in wheat water consumption varied greatly at different stages: approximately 75% at the seedling stage and reduced to about 10% at the maturity stage [39]. In addition, soil hydraulic properties also affect soil water storage [40]. Therefore, the specific path of the influence of groundwater depth and nitrogen application amount on soil water storage needs to be further studied.

4.2. Residual Soil Nitrate Accumulation Affected by Groundwater Depth, Nitrogen Application Amount

We observed that the soil nitrate content in the summer maize and winter wheat fields was affected directly by groundwater depth and nitrogen application amount. Nitrogen application largely increased the nitrate content in the soil profile, and the nitrate would accumulate in the soil profile which ultimately increased the potential risk of groundwater nitrate contamination [31,41]. Our results further confirmed that soil nitrate content at the soil–water interface decreased with the increase in groundwater depth. One reason is that the deeper groundwater depth lengthened the nitrate migration path, because nitrate migration must be driven by water [15]; therefore, it is more difficult for nitrate to migrate to the soil–water interface, and it may then accumulate in the soil profile [31]. The second reason is that crops may assimilate nitrate and microorganisms may assimilate nitrate, converting it to organic nitrogen by nitrogen fixation, reduction of nitrate to ammonium (DNRA), chemoautotrophic denitrification via sulfur or iron oxidation, anaerobic ammonium oxidation transformation of nitrate into N_2O, NO, and N_2 by denitrification [14]. Meanwhile, we also observed that increased groundwater depth would significantly aggravate the accumulation of nitrate in the soil profile but decrease the residual soil nitrate accumulation in the deep soil profile. The vadose zone acts as a buffer and filter zone in which water flow and solute transport are attenuated, and pollutants are absorbed, degraded, and transformed. It plays an important role in protecting the quality and quantity of groundwater resources [42]. As we know, the vadose zone is a globally significant store of nitrate [43]; a larger vadose zone thickness indicates a greater storage capacity of nitrate which delays the nitrate travel time from the root zone to the aquifer [44]. The storage capacity of nitrate and nitrate travel time in the unsaturated zone is mainly related to soil texture, vadose zone thickness, land use, climate, and water input [17,19,45,46]. The average nitrate transport rates through the vadose zone lag behind that of water [15]. Moreover, the response of groundwater to surface solutes is closely related to the travel time through the unsaturated zone [47].

SEM showed that the nitrogen application amount not only exhibited a directly positive effect on the residual soil nitrate accumulation, but also indirectly influence it by regulating soil total nitrogen. Groundwater depth only exhibited a directly negative effect on residual soil nitrate accumulation. Soil depth had an indirect positive effect on residual soil nitrate accumulation through the regulation of soil water storage. In addition, the specific path of groundwater depth and nitrogen application amount on the residual soil nitrate accumulation of different crops were slightly different. Nitrogen application will directly change soil nitrate and total nitrogen in different soil layers, thereby affecting the residual soil nitrate accumulation [48]. Groundwater depth can affect soil salt content and soil water content, which in turn affect crop growth [22,29,49]. It can also regulate soil nitrate and water by affecting the soil nitrate and water absorption of crops [25,33], thereby affecting the residual soil nitrate accumulation. Therefore, groundwater depth and nitrogen application act simultaneously and synergistically to affect the migration of nitrate and water. More local environmental conditions, such as groundwater depth, soil conditions, and crops, should be considered to enrich our understanding of the factors affecting residual nitrate accumulation in soil profiles.

4.3. Research Limitation and Future Perspectives

Together, our study provides first-hand evidence that groundwater depth and nitrogen application amount jointly regulate the residual soil nitrate accumulation in agricultural soil rotated with winter wheat and summer maize. We highlight that local environmental conditions, including groundwater depth, soil texture, land use, climate, and water input, should be considered to enrich our knowledge of the impact of residual soil nitrate accumulation in soil profiles. It is notable that our study only selected two nitrogen application amounts and three groundwater depths, which may result in probably biased results. Therefore, more nitrogen application amounts, and groundwater depths should be considered in further research to elucidate the intrinsic effects of nitrogen fertilization more accurately on agricultural ecosystems. The appropriate nitrogen application amounts that maintain sustainable agricultural development should be examined.

Furthermore, the emphasis of future research should be the use of a stable isotope to study the effects of groundwater depth and nitrogen application amount on the travel time and migration rate of nitrate and water, in combination with an analysis of denitrification functional gene diversity, soil hydraulic characteristics, and soil physical and chemical characteristics at different soil depths to reveal the microbial influence mechanisms of groundwater depth and nitrogen application amount on residual soil nitrate accumulation. It can provide theoretical support for understanding soil nitrate transport and residual nitrate nitrogen in the vadose zone, and provide a reference for guiding farmland irrigation and fertilization in the North China Region.

5. Conclusions

Dealing with the challenge of environmental changes is crucial for ensuring food and ecological environment security and promoting the green development of agriculture. Our research comprehensively evaluated the influence of groundwater depth, nitrogen application amount, and their interactions on water and residual soil nitrate accumulation in the agricultural soil profile. Our results found that the N240 application amount increased soil water storage in the summer maize and winter wheat field; the improvement effect was mainly concentrated in the soil layer below 60 cm. Nitrogen application largely increased the nitrate content in the entire soil profile, so nitrogen reduction is a direct way to reduce nitrate pollution in groundwater. Furthermore, the greater the groundwater depth, the longer the nitrate migration path. Denitrification in the deep vadose zone can prevent and eliminate nitrate nitrogen accumulated in the soil, and effectively reduce the risk of nitrate pollution in the groundwater. The residual soil nitrate accumulation in the entire soil profile of the winter wheat season with nitrogen application was 76.05–130.11 kg ha^{-1} higher than that of summer maize. Groundwater depth and nitrogen application amount could directly affect residual soil nitrate accumulation in agricultural soil and indirectly influence it by causing significant variations in soil nutrient and soil water storage. The nitrogen application amount had the strongest positive effects on residual soil nitrate accumulation. Together, our findings prove that groundwater depth and nitrogen application amount jointly regulate the residual soil nitrate accumulation in agricultural soil rotated with winter wheat and summer maize. Therefore, in formulating a fertilization strategy for regional agricultural green development, it is necessary to consider fertilizer application amounts and groundwater depths.

Author Contributions: F.B., X.Q. and P.L. designed this study; F.B. conducted field and laboratory experiments; F.B., X.Q. and Z.D. developed the methods; F.B., X.Q. and W.G. processed data and wrote the paper; Z.D. conducted the language editing. All authors have read and agreed to the published version of the manuscript.

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Conflicts of Interest: The authors declare no conflict of interest.

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