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Distribution of Subsurface Nitrogen and Phosphorus from Different Irrigation Methods in a Maize Field

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Abstract: With the advancement of agricultural technology, most crop cultivation adopts water-saving techniques to improve nutrient utilization efficiency. However, limited research has been carried out on the applicability of water-saving techniques for summer maize in the Shandong Province, and it is necessary to assess the risk of nutrient loss in farmland when applying these technologies. This study investigated the distribution of nitrogen and phosphorus under different irrigation methods and planting patterns through soil and water samples. It included sprinkler irrigation (SI), drip irrigation (DI), and subsurface irrigation (SUBI). Different planting patterns, i.e., monoculture (MP) and intercropping pattern (IP), were also selected in the SI zones. The results show variations in soil nitrogen distribution within the layers between 0.9 and 4.5 m, with a pronounced trend of NO_3^--N accumulating in deeper layers in the SI zone. Under SI conditions, the IP effectively reduces the nutrient accumulation around the shallow root zone while controlling the accumulation of nitrogen in deep layers. The Olsen-P accumulation in each zone would increase after the accumulation ratio decreased. Compared with MP, the depth interval of the accumulation ratio mutation was shallower in the IP. The trend of NO_3^--N accumulation in deep layers is consistent with that of nitrogen concentration in groundwater. Phosphorus that is accumulated in the deep layers is not easily leached into groundwater. In conclusion, these findings can provide basic information for irrigation management in existing cropping systems.

Keywords: soil nitrogen-phosphorus migration and accumulation; irrigation method; planting pattern; groundwater

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1. Introduction

The North China Plain is one of the most important food production regions in China, with summer maize production accounting for 35.5% of the national yield [1]. Shandong's total maize production in 2023 reached 2630.4 million tons, ranking first among the provinces in China [2]. The high yield cannot be separated from efficient water irrigation, since the shortage of water resources in the North China Plain restricts crop production [3]. Similar studies have shown that optimizing irrigation methods can effectively improve the water use efficiency, so as to alleviate the impact of water shortage [4].

Based on this issue, water-saving irrigation methods have been widely used. The subsurface drip method improves irrigation uniformity and efficiency in a number of cropping systems by applying a low volume of water at the crop root zone [5]. Liu et al. pointed out that drip irrigation significantly reduced soil water leaching, while the impact of fertilization on nitrogen leaching was minimal [6]. A good irrigation method can also improve the utilization of fertilizers and reduce nitrogen loss [7]. Sui et al. pointed out that drip irrigation could reduce deep percolation losses of water and minimize nitrogen leaching [3]. Home et al. compared the leakage of nitrogen under sprinkler irrigation (SI) and furrow irrigation, revealing a less nitrogen seepage under SI, which is a water-saving irrigation method [8]. Diversity can also enhance the efficiency of water and fertilizer use while reducing nutrient loss [9]. Intercropping is a common planting pattern that can improve the sustainability of crop production with low inputs [10]. Fan et al. found that intercropping with maize improved the water use efficiency by 14% compared to monoculture. Furthermore, in the later stages of cultivation, it is possible to reduce irrigation inputs moderately, which can help minimize nutrient loss [11].

Soil nitrogen and phosphorus migration is often accompanied by water loss. While nitrogen is not absorbed promptly by the crop roots, the residual nitrogen is easily migrated with runoff [12]. Nitrogen that migrated to deeper soil may further leaching through infiltration, ultimately resulting in groundwater pollution [13]. Phosphorus primarily tends to be lost through surface runoff rather than leaching. Phosphorus exhibits a strong affinity for soil particles; however, once phosphorus fixation reaches saturation, there exists a significant probability of downward leaching [14]. Phosphorus loss through leaching typically occurs only when mobile phosphorus compounds are present in the soil and under certain hydraulic conditions [15]. The Olsen method, which is widely used in the world, has become a unified method for the determination of available phosphorus within the soil [16,17]. Meanwhile, Olsen-P in phosphorus fertilizers can be directly absorbed by crops, and its accumulation can be used to represent soil phosphorus loss. When Olsen-P accumulation is high, it is more prone to inducing non-point phosphorus source pollution [18]. Sun et al. pointed out that high levels of Olsen-P in the soil can have adverse effects on surrounding water [19]. In the simulation test of undisturbed soil leakage, Turner et al. found that the proportion of total dissolved phosphorus (TDP) in soil phosphorus leakage was relatively large [20]. Groundwater is commonly used for irrigation. However, irrigated water with poor quality can inhibit crop growth, resulting in permeability reduction, salinization, and other problems [21]. In addition, when groundwater serves as a source of drinking water, a high concentration of NO_3^--N can lead to impaired bodily functions and even induce cancer [22]. Studies on water-saving irrigation methods and intercropping modes on water and fertilizer control have always been a hot topic, but there are still few comparative studies among various water-saving irrigation methods, and their adaptability in maize growing areas still needs to be studied. In addition, the synergistic effect of the intercropping pattern and water-saving irrigation is also a problem worth thinking about.

This study focuses on a summer maize field within the Yellow River irrigation region. Based on the sampling data, the distributions of subsurface nitrogen and phosphorus under the influence of different water-saving irrigation methods and different planting patterns were studied. The water-saving irrigation methods comprised sprinkler irrigation (SI), drip irrigation (DI), and subsurface irrigation (SUBI), and the planting patterns consisted of monoculture (MP) and an intercropping pattern (IP). Based on the sampling data, the influence of nitrogen and phosphorus accumulation levels was analyzed. In the Conclusions section, we propose suggestions for efficient irrigation management for reducing further contamination.

2. Materials and Methods

2.1. Experimental Site and Field Management

The experimental site is situated in Modern Agricultural Industry Park (116°39′ E, 36°40′ N) in Qihe County, Shandong Province. In July 2023, Qihe County had an average temperature of 28.2 °C and received an average rainfall of 102.5 mm during the study period. The soil at the experimental site was Fluvo-aquic soils, with organic matter content of 12.58 $g \cdot kg^{-1}$, bulk density of 1.38 $g \cdot cm^{-3}$, Olsen-P content of 9.8 $mg \cdot kg^{-1}$, available nitrogen content of 53.25 $mg \cdot kg^{-1}$, and PH of 7.8 (0.3 m depth).

The experimental site is predominantly characterized by quaternary loess deposits with a yellow-brown hue. Most of the loess are silty and clay, and the clay has more viscous particles, which reduces the permeability. Additionally, localized occurrences of coarse sand intercalations are observed, with thickness ranging approximately from 80 to 280 m [23].

The study field implements a crop rotation system between wheat and maize. For this study, summer maize was planted in mid-June 2023. The row spacing was about 20 cm with seedling density of 7–8 plants·m^{-2}. Irrigation in this field primarily relies on groundwater. As shown in Figure 1, three types of water-saving irrigation methods were adopted in this field. Based on these methods, the field is divided into three zones: the SI zone, DI zone, and SUBI zone. Further subdivision of the SI zone into Zone 1 and Zone 2 is based on different planting patterns, with Zone 1 employing a monoculture maize pattern (MP) and Zone 2 adopting a maize–soybean intercropping pattern (IP). According to the drilling results, the soil textures in the vadose zone across the different zones are primarily composed of clay, silty clay, silty, and another silty clay layer, which are shown in Table 1.

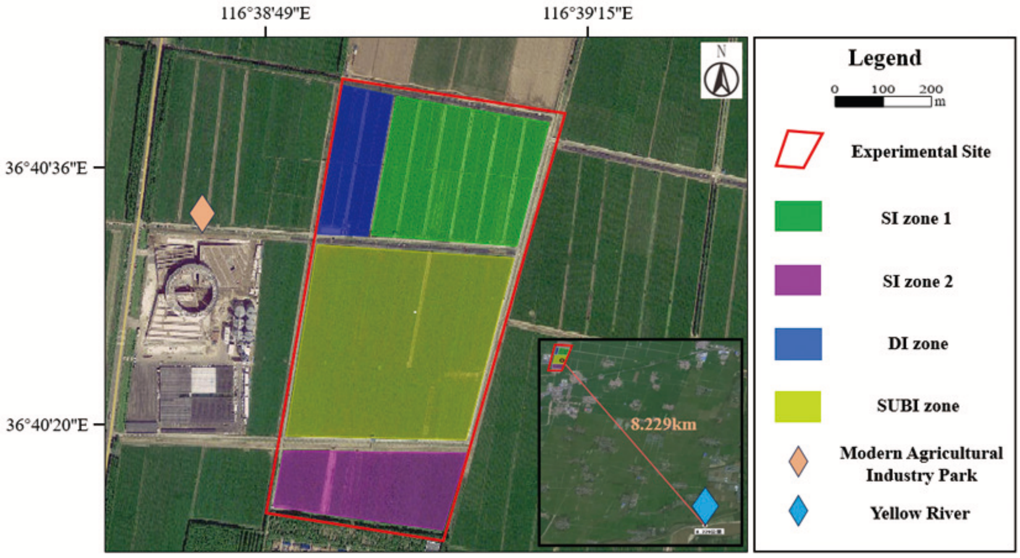

Figure 1. Geographical location and field management.

Table 1. Stratigraphic distribution corresponding to different zones. The depth ranges in the table are measured in meters (m).

Zone	Clay	Silty Clay	Silty	Silty Clay
SI Zone 1, DI zone	0–0.3	0.3–1.8	1.8–3.2	3.2–5.0
SI Zone 2	0–0.4	0.4–1.2	1.2–2.4	2.4–5.0
SUBI zone	0–0.3	0.3–0.9	0.9–3.4	3.4–5.0

2.2. *Experiment Treatment and Sampling*

Based on the division into the four zones previously described, four distinct treatments were defined. Phosphorus fertilizer was applied once as a basal dose for each treatment, while nitrogen fertilizer was applied in three stages: 20% before sowing, 50% from the jointing to the tasseling stage, and 30% during the grain-filling stage. The application amount was N 290 kg·hm^{-2}, P_2O_5 115 kg·hm^{-2}, and K_2O 175 kg·hm^{-2}. Experimental treatments are shown in Table 2.

Table 2. The irrigation volume per acre for different treatments, along with the corresponding planting pattern and soil sampling points.

Treatment	Irrigation Volume (m^3·hm^{-2})	Planting Pattern	Soil Sampling Point
SI Zone 1	40	MP	T1, T2
SI Zone 2	40	IP	T3, T4
DI zone	25	MP	T5, T6
SUBI zone	23	MP	T7, T8

The samples were collected in late July 2023, during the maize growth stage from jointing to tasseling. This critical period is characterized by the maize's increasing demand for nutrients and water. In this study, it is imperative to conduct soil sampling at the maximum possible depth to encompass all soil textures present in the vadose zone, thereby facilitating a more comprehensive analysis of the impact of nitrogen and phosphorus accumulation in the deep vadose zone on groundwater quality. Consequently, based on the soil texture distribution illustrated in Table 1, the sampling depth was established at 0–4.5 m. Given the presence of silty clay at the site known for its poor permeability, drilling was stopped around 4.5 m at this layer clay for all boreholes. To have more representative samples, two boreholes were dug at each sampling point to collect cluster samples [24]. The soil samples were collected at ten depth intervals of 0–0.15 m, 0.15–0.30 m, 0.30–0.60 m, 0.60–0.90 m, 0.90–1.50 m, 1.50–2.10 m, 2.10–2.70 m, 2.70–3.30 m, 3.30–3.90 m, and 3.90–4.50 m. Soil cluster samples from the same depth of the two boreholes were mixed and then stored at a low temperature before being sent for laboratory analysis. Total nitrogen (TN), ammonium nitrogen (NH_4^+-N), nitrate nitrogen (NO_3^--N), available phosphorus (Olsen-P), and water-soluble phosphorus (WSP) were all analyzed.

Based on site conditions, seven groundwater samplings points were established along the north–south trend of the Yellow River, denoted as S1 to S7. Groundwater samples were mainly collected from irrigation wells and monitoring wells in the field. Additionally, surface water sample were collected along the Yellow River at sampling point S8. Groundwater samples were collected using bailers for on-site measurement of total dissolved solids (TDS). Then, the samples were preserved at a low temperature and sent to the laboratory for analysis of total nitrogen (WTN), nitrate nitrogen (NO_3^--N), and total dissolved phosphorus (TDP). The arrangement of water sampling points is illustrated in Figure 2.

Olsen-P was extracted with 0.5 mol·L^{-1} $NaHCO_3$ and analyzed with a UV-visible spectrophotometer [25]. TN was determined by the automatic Kjeldahl apparatus method [26]. NH_4^+-N and NO_3^--N were extracted with 50 mL of 1 mol·L^{-1} KCl and measured using an auto analyzer [27]. WTN was analyzed with the alkaline potassium persulfate UV spectrophotometer method [28]. NO_3^--N in water sample was measured by ultraviolet spectrophotometry [29]. TDP was analyzed with the ammonium molybdate spectrophotometer method [30].

2.3. Statistical Analysis

The distribution of nitrogen and phosphorus in the soil profile was represented by a line chart. Soil sampling data were subjected to analysis of variance (one-way ANOVA) to verify the significance of the difference between treatments. Correlation analysis was used to examine the relationship between the NO_3^--N/Olsen-P and the cumulative Olsen-P. Statistical analyses were carried out using SPSS 25 software.

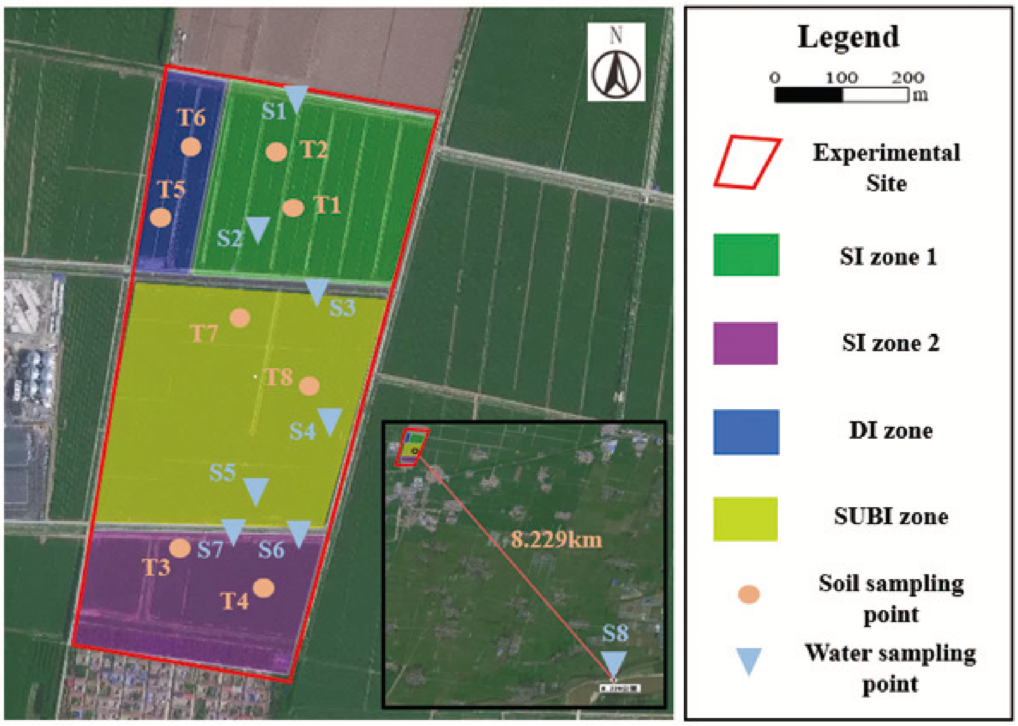

Figure 2. Arrangement of sampling points.

3. Results and Discussion

3.1. Nitrogen Distribution under Different Irrigation Methods

The distribution of nitrogen and phosphorus was analyzed based on soil sampling points associated with corresponding treatment. MP was adopted in the SI Zone 1, DI zone, and SUBI zone. In these three zones, the vertical distribution of TN within the depth ranging from 0 to 4.5 m exhibits a consistent pattern of "decrease first, then increase". The concentration of TN in the shallow layers (0–0.9 m) remained greater than 0.5 g·kg^{-1}, with the sampling phase aligning with the tasseling stage of maize, when the roots exhibited a heightened need for nutrients. Most of the input nitrogen elements were transformed and immobilized within the shallow layers, waiting to be absorbed by the roots. In the topsoil layers ranging from 0 to 0.9 m, accumulated nitrogen has the probability of being transported along with runoff before absorption. Subsequently, at depths exceeding 0.9 m where the density of maize root systems diminishes, it gradually emerges with the discernible impacts of various irrigation techniques on the migration and retention of nitrogen. Figure 3 shows that in the depth range of 2.1 to 4.5m, the accumulation of TN is more pronounced in the SI Zone 1.

Following two rounds of fertilization, the accumulation of available nitrogen (NH_4^+-N and NO_3^--N) within the 0-0.3 m soil layer increased. Figure 4 shows low levels of NH_4^+-N accumulation in the soil, with slight fluctuations in concentration, but with all of them being below 10 mg·kg^{-1}, with the SI Zone 1 exhibiting the most substantial accumulation. In contrast, the accumulated NO_3^--N in the soil layers of all zones is higher, with noticeable fluctuations during downward migration (Figure 5). In the shallow soils of the experimental site, which exhibit weak alkalinity based on soil pH, the rate of soil mineralization is lower than the rate of nitrification. This discrepancy promotes the accumulation of NO_3^--N [31,32]. Under identical conditions, the distribution of NO_3^--N in the soil layer below 0.9 m is more pronounced than NH_4^+-N. NO_3^- carries a negative charge, making it more likely to be repelled by soil particles, preventing stabilization and enabling it to migrate with runoff. On the other hand, due to its positive charge, NH_4^+-N tends to be held on the soil exchange complexes and does not move with water. Particularly when the accumulation of NO_3^--N exceeds that of NH_4^+-N, it is more likely to migrate to greater depths due to water flow. Additionally, as NO_3^- migrates downward, changes in soil texture occur, affecting the rate of NO_3^- migration due to changes in soil permeability. Therefore, under the same hydraulic conditions, the migration trend and fluctuation in accumulation of NO_3^- are more pronounced. For the DI zone and SUBI zone, there is a notable decrease in the accumulated amount after the occurrence of higher accumulation peaks, with no increase occurring within the range of 3.9–4.5 m (Figure 5b,c). Conversely, the SI zone does not show accumulation peaks, while the accumulation of NO_3^--N in the entire soil layer shows no significant decrease, and there is still a growing trend observed in the range of 3.9–4.5 m (Figure 5a). Within the DI and SUBI zones, the low irrigation intensity leads to an accumulation of the concentration of NO_3^--N above the 2.7 m soil layer over the same time period. Conversely, in the SI Zone 1, which is characterized by a relatively high irrigation intensity, NO_3^--N tends to migrate continuously to soil layers below 2.7 m. Consequently, the accumulation phenomenon above 2.7 m is less pronounced in the SI zone compared to the other two zones. The results showed that NO_3^--N migrated and accumulated in the soil below 0.9 m under different irrigation methods. With the increase in irrigation, there is a greater tendency for NO_3^--N to migrate to deeper soil layers. Sharmasarkar et al. also found that flood irrigation with a higher intensity tends to cause more NO_3^--N migration to deeper layers compared to DI [33]. In addition, when the groundwater depth in the SI zone is relatively shallow, there is also a higher risk of leakage into the groundwater, causing further pollution.

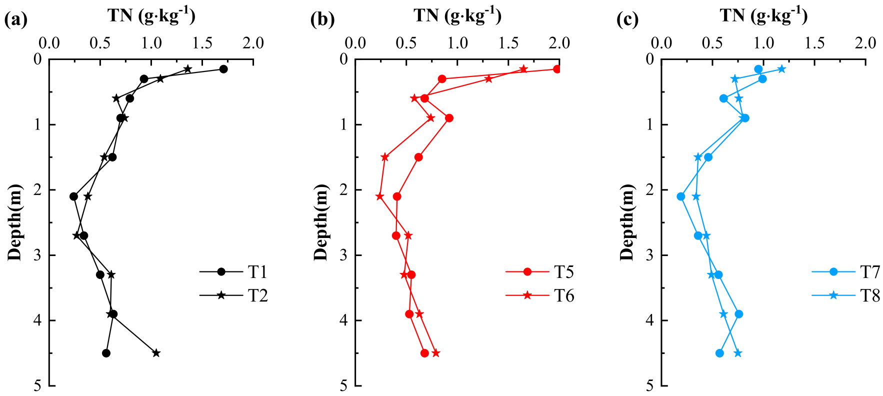

Figure 3. Vertical distribution of TN under different treatments (**a**) SI Zone 1: T1 and T2; (**b**) DI zone: T5 and T6; (**c**) SUBI zone: T7 and T8; Figures 4–7 use the same drawing method).

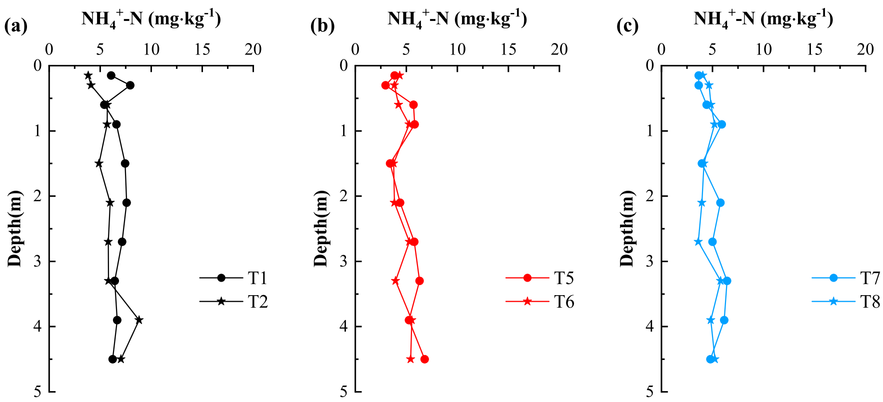

Figure 4. Vertical distribution of NH_4^+-N under different treatments: (**a**) SI Zone 1, (**b**) DI zone, and (**c**) SUBI zone.

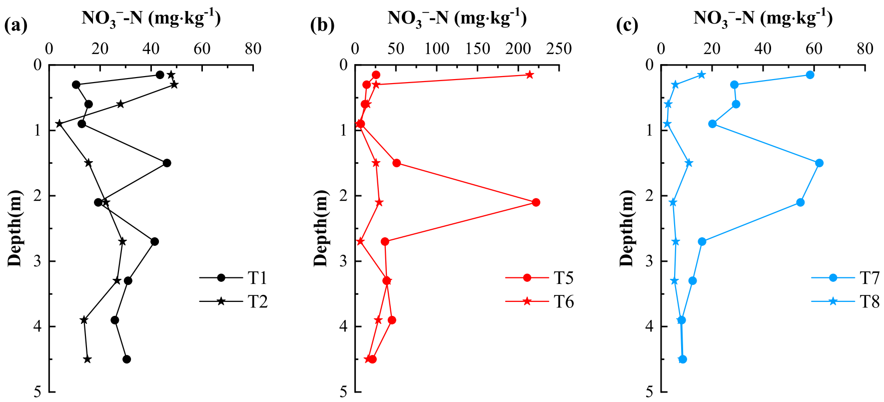

Figure 5. Vertical distribution of NO_3^--N under different treatments: (**a**) SI Zone 1, (**b**) DI zone, and (**c**) SUBI zone.

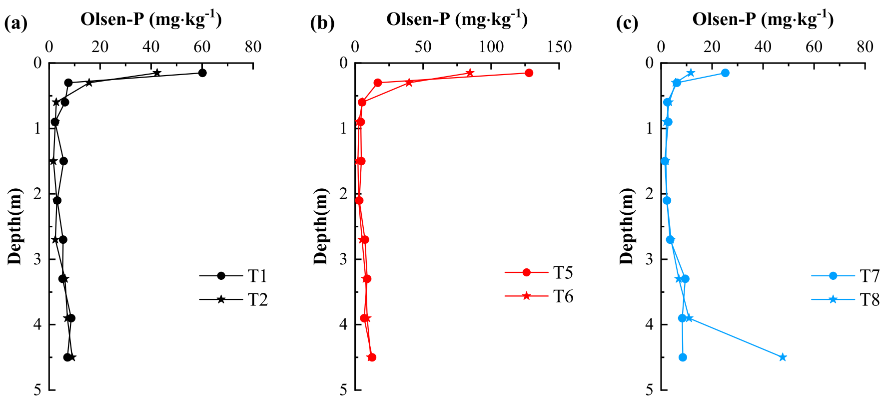

Figure 6. Vertical distribution of Olsen-P under different treatments: (**a**) SI Zone 1, (**b**) DI zone, and (**c**) SUBI zone.

3.2. Phosphorus Distribution under Different Irrigation Methods

Under each irrigation method, the Olsen-P distribution is mainly concentrated within 0-0.6 m, except for the depth of 4.5 m at T8. Tang et al. obtained the threshold for downward leaching of Olsen-P from 20 to 30 mg·kg^{-1} by fertilization experiments in Fluvo-aquic soil within a wheat–maize rotation zone [34]. Figure 6 shows that the accumulation of Olsen-P in the shallow soil of the SI Zone 1 and DI zone exceeded the threshold value, but no significant accumulation was found in the soil below 0.6m after two rounds of irrigation. The surface soil in the experimental site is mostly characterized by clay and silty clay. Clay has a major role in soil aggregation, being able to promote soil and water conservation, as well as having the ability to stop Olsen-P leaching into the subsoil [35]. Compared to NO_3^--N, Olsen-P is more likely to be fixed by soil. Only a small portion of Olsen-P migrates to deeper soil layers for accumulation. Moreover, the influence of different irrigation methods on Olsen-P migration and accumulation is similar in most ranges. The accumulation of Olsen-P in soil layers can serve as an indicator for evaluating phosphorus leaching [36,37], which also reflects the less pronounced trend of phosphorus leaching under various water-saving irrigation methods.

3.3. Differential Analysis of Nitrogen and Phosphorus Distribution

Different trends in the vertical distribution of soil nitrogen and phosphorus within soil layers below 0.9 m are shown in Figures 3–6. These trends are attributed to the dense distribution of crop roots and the influence of transpiration in the shallow soil layer, which can affect soil moisture distribution. Based on these responses, the sampling depth is divided into two intervals (0–0.9 m and 0.9–4.5 m) for conducting the quantitative differential analysis of nitrogen and phosphorus vertical distribution under different irrigation methods. For nitrogen differential analysis, the main focus is on NH_4^+-N and NO_3^--N. For phosphorus, considering that Olsen-P accumulation includes WSP, and it is the primary phosphorus form absorbed by crops, the phosphorus differential analysis focuses on Olsen-P.

In the analysis of the NH_4^+-N distribution (Figure 7a), differences are observed between the SI Zone 1 and the other two zones within both intervals, while differences between the DI and SUBI zones are less pronounced. This further indicates that even the NH_4^+-N distribution levels are relatively low across all zones, and the effect of irrigation in NH_4^+-N on the distribution can still be observed. In the differential analysis of the NO_3^--N distribution (Figure 7b), there was no significant difference in the range of 0–0.9 m among the three irrigation methods. However, obvious differences were observed between the DI and SUBI zones in the range of 0.9–4.5 m, indicating that as soil depth increases, differences in NO_3^--N migration and accumulation occur even though the amount of irrigation is similar. In the differential analysis of the Olsen-P distribution (Figure 7c), the differences under the various irrigation methods are not clear. This demonstrates that under the three water-saving irrigation methods in the current study, there is no clear difference in migration and accumulation of Olsen-P, and its downward trend is weaker than that of NO_3^--N.

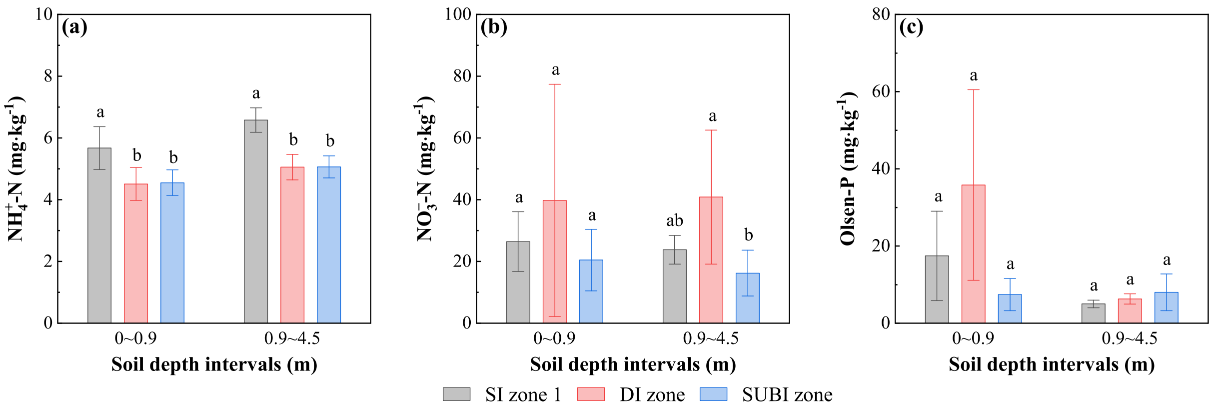

Figure 7. Differences in the vertical distribution of of soil nitrogen and phosphorus under different treatments: (**a**) NH_4^+-N, (**b**) NO_3^--N, and (**c**) Olsen-P. The differential analysis was conducted across two distinct depth intervals (0–0.9m and 0.9–4.5m). The different letters above the bars represent significant differences at the level of $p < 0.05$.

3.4. Nitrogen and Phosphorus Distribution under Different Planting Patterns

To analyze the synergistic effects of the IP and irrigation method, the distribution of soil nitrogen and phosphorus under different planting patterns across two distinct treatments in the SI zones were analyzed. Compared to MP, in the IP of SI Zone 2, the accumulated amounts of NH_4^+-N and NO_3^--N along the soil profile decreased. The NO_3^--N in deeper layers is generally below 20 mg·kg^{-1}, without evident accumulation peaks (Figure 8a,b). Figure 8c demonstrates that the distribution pattern of Olsen-P in the SI zones is consistent across different planting patterns. This is because arbuscular mycorrhiza colonize the roots of plants. Compared to MP, the arbuscular mycorrhizal network can be formed effectually between the roots of soybean and corn, and mycorrhiza can expand the nutrient intercepting area to control nutrient leaching loss after irrigation and rainfall [38,39].

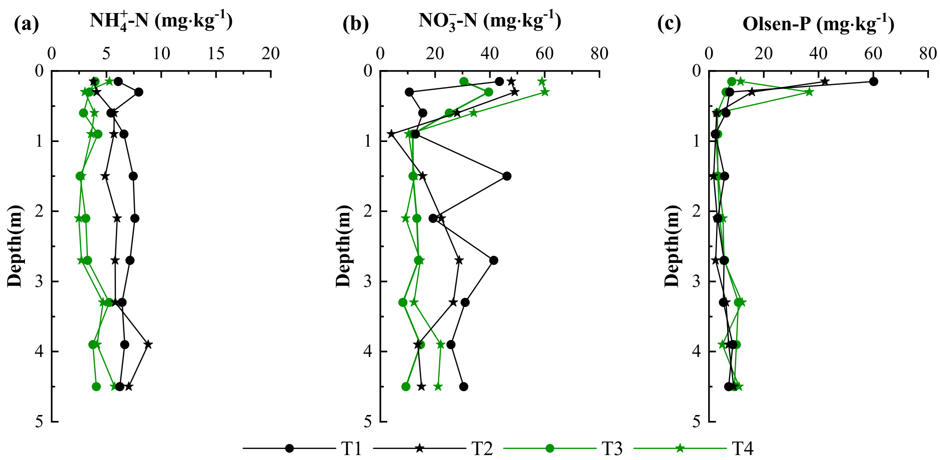

Figure 8. Vertical distribution of soil nitrogen and phosphorus under different treatments (SI Zone 1: T1 and T2; SI zone 2: T3 and T4) : (**a**) NH_4^+-N, (**b**) NO_3^--N, and (**c**) Olsen-P.

The vertical distribution of nitrogen below 0.9 m in the two SI zones shows significant differences (Figure 9a,b). Based on the experiment of maize and soybean intercropping, Du et al. concluded that the IP can effectively improve nitrogen usage compared with MP [40]. The IP improved the absorption activity of maize roots and enabled the crops to absorb nitrogen effectively in the root zone. Therefore, under the same sprinkler-irrigated method, the nitrogen migrating deep with water in SI Zone 2 was reduced. This indicates that the IP has a certain control on the deep migration of soil nitrogen. The decrease in Olsen-P accumulation within the 0–0.6 m is attributed to the facilitative effect of the IP, which allows for timely phosphorus absorption by crops. The experiments by Qin et al. also show that the IP of maize and soybean can increase the absorption efficiency of phosphorus fertilizer by crops [41]. Figure 9c indicates that there is no significant difference in the vertical distribution of Olsen-P between the two depth intervals. Therefore, in the synergistic effect of SI and the IP, the accumulation of nitrogen and phosphorus in shallow layer was controlled, and the IP could effectively alleviate the situation regarding nitrogen being easily migrated in the deep layers under SI.

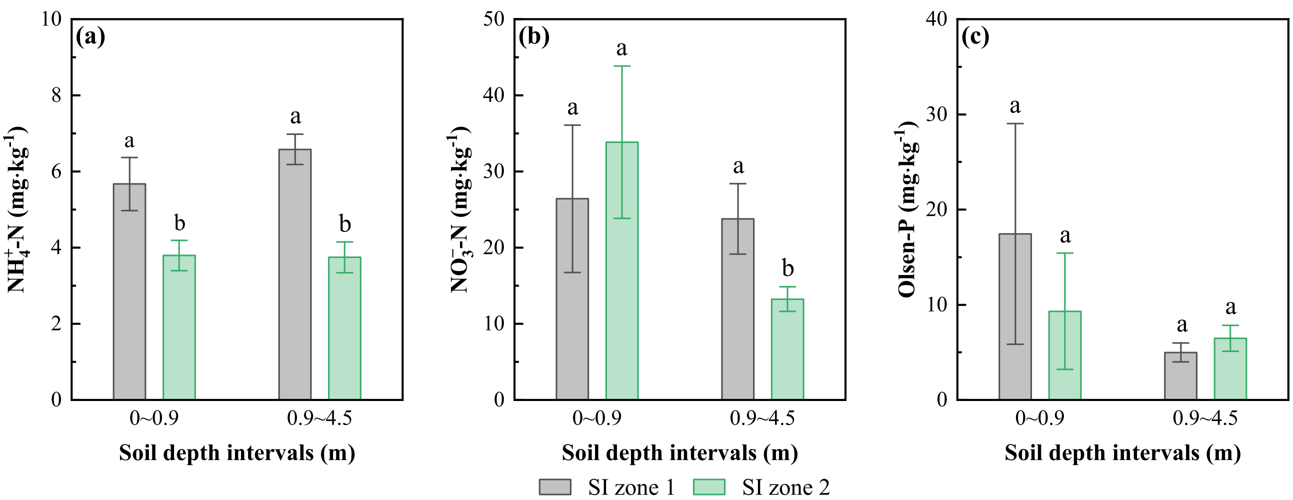

Figure 9. Differences in the vertical distribution of of soil nitrogen and phosphorus under different treatments : (**a**) NH_4^+-N, (**b**) NO_3^--N, and (**c**) Olsen-P. The differential analysis was conducted across two distinct depth intervals (0–0.9m and 0.9–4.5m). The different letters above the bars represent significant differences at the level of $p < 0.05$.

3.5. Impact of NO_3^--N/Olsen-P Ratio on Cumulative Olsen-P

NO_3^--N and Olsen-P are the main forms of nitrogen and phosphorus absorbed by crops. The balance of their accumulation in the soil affects the distribution and absorption of nutrients. The changes in their ratio can influence the physical and chemical properties of soil, which in turn affect the release and absorption of phosphorus [35]. Based on the distribution of NO_3^--N and Olsen-P, the accumulation ratio of average cumulative NO_3^--N to average cumulative Olsen-P (NO_3^--N/Olsen-P) is selected for correlation analysis to further analyze the impact of spatial variability in the accumulation ratio on the distribution of Olsen-P. The average cumulative Olsen-P and the accumulation ratio within a soil depth of 0–0.9 m, 0.9–4.5 m and 0–4.5m are selected for correlation analysis. First of all, for depth intervals above 0.9 m, a significant negative correlation ($p < 0.05$) is observed in SI Zone 1. For depths below 0.9 m, negative correlations ($p < 0.01$, $p < 0.05$, $p < 0.01$) are observed in the SUBI zone, SI Zone 1, and Zone 2. Furthermore, when considering the entire depth range from 0 to 4.5 m, a negative correlation ($p < 0.01$) is observed in all zones, with correlation coefficients of −0.718, −0.582, −0.616, and −0.636 (Table 3).

Table 3. Correlation analysis of average cumulative Olsen-P and accumulation ratio in different depth intervals under different irrigation conditions. In the table, * indicates a significance level of $p < 0.05$, and ** indicates $p < 0.01$; p can characterize whether the analysis is statistically significant. The absence of * indicates that the correlation is not significant.

Depth Intervals	SI Zone 1	DI Zone	SUBI Zone	SI Zone 2
0–0.9 m	−0.714 *	−0.600	−0.095	−0.563
0.9–4.5 m	−0.529 *	−0.462	−0.803 **	−0.829 **
0–4.5 m	−0.718 **	−0.582 **	−0.616 **	−0.636 *

In order to better describe the distribution of data, according to the following formula—$(X\text{-}u)/\theta$—the accumulation ratio and the average cumulative Olsen-P in Figure 10 were normalized, where X represents the original value, u represents the average value, and θ represents the standard deviation.

As shown in Figure 10, it can also be observed that the accumulation ratio first shows an increasing and then decreasing trend. In the shallow soil range (from 0 to 0.9 m), phosphorus is easily fixed and absorbed, resulting in a larger decrease compared to NO_3^--N, leading to an increase in the accumulation ratio. Under the influence of the three chosen irrigation methods, the peak value of the accumulation ratio was in the soil layer range of 0.9–2.7 m, as indicated in Figure 10a–c. From the above analysis, it can be seen that in MP, NO_3^--N in all zones displays obvious accumulation in this range, while the accumulation of Olsen-P in this range is low. With the increase in depth, when the accumulation ratio decreased, Olsen-P accumulation gradually increased.

Because the higher accumulation level of NO_3^--N may occupy adsorption points of Fe and Al oxides in the soil, it reduces the points available for phosphorus fixation [42]. This can facilitate the migration and loss of phosphorus. Therefore, the accumulation degree of Olsen-P in the soil layer below 2.7 m is greater than that in shallow soil. Due to the influence of the irrigation method, the depth of the soil layer in SI Zone 1 is greater than that in the DI zone and SUBI zone when the accumulation ratio changed abruptly. However, when SI and the IP were synergized, the accumulation ratio changed abruptly in the soil layer around 0.9m, and, correspondingly, cumulative Olsen-P also increased from 0.9 m in SI Zone 2 (Figure 10d). This is because under the IP, the migration and accumulation of NO_3^--N in the range below 0.9 m was effectively controlled, resulting in a cumulative trend of an increase in Olsen-P in the shallow range. However, due to the effect of the IP, most of Olsen-P was fixed and absorbed, so there was no obvious deep accumulation of Olsen-P. Therefore, under the influence of different irrigation methods and planting patterns, when the accumulation ratio (NO_3^--N/Olsen-P) decreases significantly, Olsen-P tends to accumulate to the deep layer. When the irrigation method or planting pattern changes, the depth of the mutation of the accumulation ratio also changes accordingly.

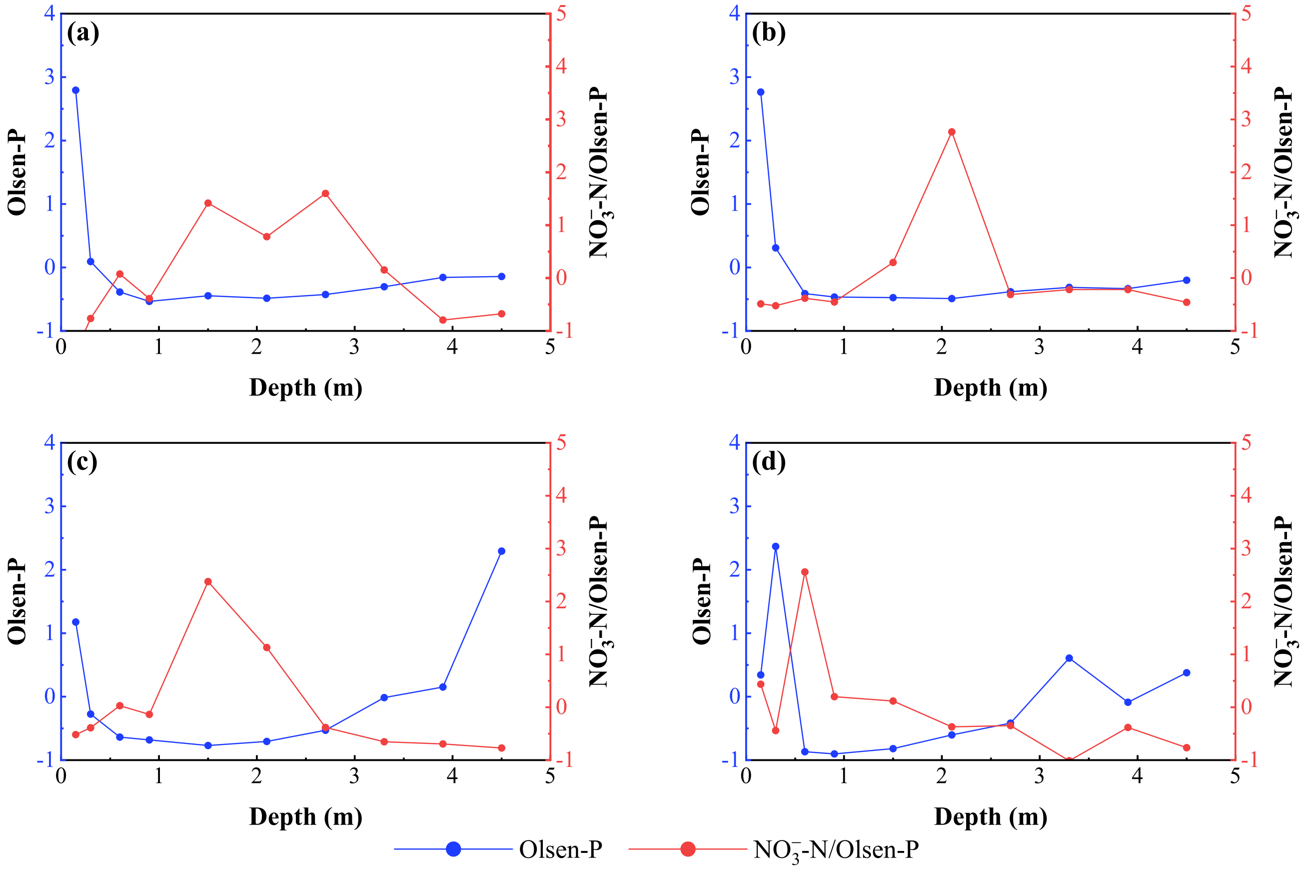

Figure 10. Distribution of average cumulative Olsen-P and accumulation ratio: (**a**) SI Zone 1, (**b**) DI zone, (**c**) SUBI zone, (**d**) and SI Zone 2.

3.6. Impact of Nitrogen and Phosphorus Accumulation to Groundwater

In the deep soil layer, nitrogen and phosphorus accumulation existed in different degrees under the three water-saving irrigation methods or in the SI zone with the IP. In order to analyze the impact of spatial differences of nitrogen and phosphorus accumulation to groundwater, soil sample indexes of 4.5 m depth and corresponding water sample indexes in different zones were combined for analysis.

As shown in Figure 11, the groundwater depth was around 8 m below the ground surface. The concentrations of WTN, NO_3^--N, and TDS at S2 and S3 were significantly higher. These two points correspond to the south side of SI Zone 1. The concentrations of WTN, NO_3^--N, and TDS were lower in the SUBI zone and SI Zone 2. Additionally, it can be observed that the trends in the concentrations of WTN and NO_3^--N are consistent. Similar studies have confirmed that NO_3^--N is the main form of groundwater nitrogen pollution [43]. Compared with nitrogen, the concentration of TDP in the water samples is noticeably lower, and there is little variation in TDP among the sampling points. Based on the criteria for water chemistry indicators, the concentrations of WTN and NO_3^--N in the water samples are both below 15 $mg\cdot L^{-1}$, satisfying the Class III water limit (20 $mg\cdot L^{-1}$) in the standard for groundwater quality [44]. Additionally, the TDS values are all below 2000 $mg\cdot L^{-1}$, satisfying the Class IV water limit. The maximum concentration of TDP in the water samples is 0.08 $mg\cdot L^{-1}$, since groundwater and surface water are interconnected, according to the Class II water limit (0.1 $mg\cdot L^{-1}$) in environmental quality standards for surface water [45], the TDP at S8 meets the requirement. WTN is slightly higher than the indicators at some groundwater sampling points, exceeding the Class V water limit for groundwater quality by 0.31 times. Considering that the study field is not the only field where water samples are collected from the Yellow River, the pollution of irrigation water quality in the study field is still mainly based on groundwater quality. However, further control is needed in water and fertilizer management.

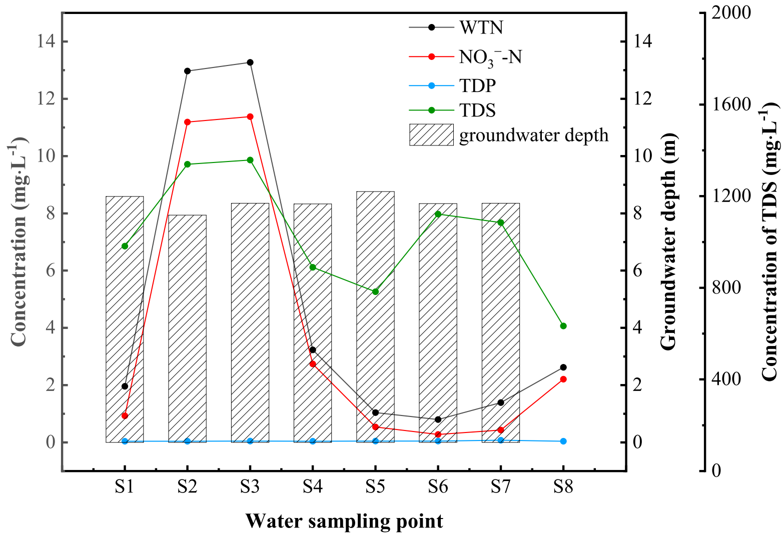

Figure 11. Results of groundwater hydrochemistry in the study field: The vertical axis on the left represents the concentrations of WTN, NO_3^--N, and TDP, while the vertical axis on the right represents the groundwater depth and TDS concentration. The horizontal axis represents the sampling points.

The trend of TN in the soil does not align with the trend of WTN (Figure 12a) for the reason that TN includes forms of inorganic nitrogen and organic nitrogen besides NO_3^--N. NO_3^--N is the most easily lost form among all forms of nitrogen. Other forms of nitrogen in the soil have a certain probability to be converted into NO_3^--N during the migration process, so even if the accumulation of TN is high, it does not necessarily mean that a large amount of other forms of nitrogen will be converted into NO_3^--N and enter into the groundwater. NO_3^--N in deep soil layers at different locations is generally consistent with the distribution trend of NO_3^--N in water samples (Figure 12b). This indicates that the accumulation of NO_3^--N in the soil has an influence on the concentration of NO_3^--N in water samples. Soluble total nitrogen is easily lost due to its inorganic form with runoff, and the main loss form is NO_3^--N [46]. Based on the samples, it can be inferred that most nitrogen forms in groundwater are NO_3^--N. Therefore, it is necessary to consider the accumulation level of NO_3^--N in deep soil layers when assessing the impact of soil nitrogen on groundwater. TN accumulation significantly decreases in the vicinity of S1 and S2 (Figure 12a,b). However, the proportion of NO_3^--N accumulation notably increases. Meanwhile, there is a noticeable increase in WTN and NO_3^--N concentrations in water samples. This further demonstrates that nitrogen loss from the soil is mainly NO_3^--N, and the area around S1 and S2, located in SI Zone 1, indeed exhibits a priority for NO_3^--N loss. In contrast, even when soil nitrogen accumulation increases near S6 and S7 in SI Zone 2, the corresponding groundwater sample does not show significant fluctuations (Figure 12b). This indirectly proves the effective nitrogen-fixing role of the IP.

Regardless of soil phosphorus fluctuations, the concentration of TDP in water samples does not show obvious fluctuations. Even when soil phosphorus suddenly increases near S4, there is no increase in the TDP concentration (Figure 12c). It is suggested that phosphorus does not easily leak into groundwater, even if it migrates to deeper soil layers with runoff. Previous conclusions also confirmed that subsoil has a sufficient capacity to adsorb and hold phosphorus, making it difficult for phosphorus to flow into groundwater [47].

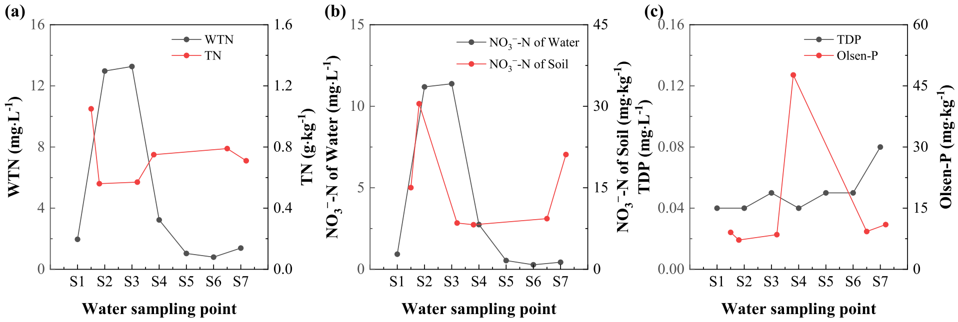

Figure 12. The distribution of some indexes in groundwater samples and the distribution of nitrogen and phosphorus in the deep soil layer (4.5 m) at adjacent points. The TN of the soil sample is equivalent to the WTN of the water sample (**a**), while the NO_3^--N content in the soil sample corresponds to that in the water sample (**b**), and the Olsen-P in the soil aligns with the TDP of the water sample (**c**).

4. Conclusions

In this research, we study the migration and accumulation of nitrogen and phosphorus under different water-saving irrigation methods. The impact of the IP was also discussed for SI. Finally, the risk of nitrogen and phosphorus loss in the field was further analyzed in combination with the water sample index.

Under different irrigation patterns, soil nitrogen migration and accumulation are primarily dominated by NO_3^--N, with a pronounced trend of NO_3^--N migrating to deeper soil layers observed in SI Zone 1. Significant differences in nitrogen accumulation are observed within the soil layer range of 0.9–4.5 m. The migration and accumulation trend of soil phosphorus is not obvious, and there are no apparent differences under different irrigation methods.

Adopting an IP in the SI zone effectively reduces the accumulation of nitrogen and phosphorus in the shallow root zone. Moreover, the IP can reduce the trend of nitrogen migration and accumulation in deep soil.

Under the influence of different irrigation methods and planting patterns, when the accumulation ratio decreases from the peak point, Olsen-P tends to accumulate in deeper layers. When the influence changes, the depth of the mutation of the accumulation ratio changes as well. Factors such as irrigation methods and planting patterns can indirectly affect the distribution of phosphorus by influencing the accumulation ratio.

The hydrochemical index of groundwater samples did not exceed the regulation standard. The loss of nitrogen in the deep soil layers (4.5 m) was high, particularly for NO_3^--N in SI Zone 1 with MP. This accumulation level has an impact on the nitrogen levels in groundwater. However, the accumulation level of phosphorus in deep soil layers has no significant effect on the phosphorus in groundwater. The groundwater in the field did not reach a critical level of pollution.

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