Nitrogen distribution in apple orchard soil profile under fertilization with different water and fertilizer coupling techniques

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Abstract: Optimization of water and fertilizer coupling management approaches could not only increase apple yield and quality, but also reduce the potential negative impacts of such management activities on the environment. The aim of the present study was to determine the optimal water-nitrogen (WN) coupling management strategy in an apple orchard in the Weibei Dryland, Shaanxi Province, China, under limited irrigation. A randomized complete block design was adopted to test the effects of three drip irrigation levels (W1, 300 m^3/hm^2; W2, 600 m^3/hm^2; W3, 900 m^3/hm^2) and four N application levels (N0, 0 kg/hm^2; N1, 200 kg/hm^2; N2, 400 kg/hm^2; and N3, 600 kg/hm^2) on N distribution in the 0-100 cm soil profile. Apple yield and economic benefits under different treatments were also evaluated over a three-year period (2012-2014). Compared with the N0W1 treatment, soil N contents were higher and exhibited distinct trends in the soil profile under other treatments. Overall, total N contents exhibited a downward trend from the surface to the subsurface layers (0.11-2.34 g/kg); however, the total N contents of the lower soil layer increased with an increase in irrigation amount. NO_3-N contents were the lowest in the 40-60 cm soil layer and then increased with an increase in soil depth. The highest NO_3-N contents of different soil layers were observed under the N3W3 treatment, ranging from 124.7 mg/kg (0-20 cm) to 90.9 mg/kg (80-100 cm). NH_4^+-N contents were low (<10 mg/kg), mainly accumulating in the surface layer and decreasing toward the deeper layers>20 cm. Different water-N coupling treatments also increased apple yield by 7.30%-41.62% when compared with the N0W1 treatment. The highest apple yield (three-year mean: 41.01 t/hm^2) was observed under the N2W2 treatment, with an output value of 237 900 RMB yuan/hm^2 and a net income of 232 000 RMB yuan/hm^2. Considering fruit yield, partial productivity of N fertilizer, and economic and environmental benefits, the N2W2 treatment is the optimal water-N fertilizer coupling drip irrigation scheme for apple production in the study area and other similar dryland areas.

Keywords: apple orchard, water-nitrogen coupling, nitrogen fertilization, soil profile, yield
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1 Introduction

In recent decades, nitrogen (N) fertilizer-use efficiency has been decreasing globally. In China, N recovery by crops decreased from 57% in 1979 to 43% in 1998, along with a two-fold increase in total N (TN) loss[1,2]. The continuous decline in N-use efficiency (NUE) is a major issue for all cereal and vegetable crops, as well as some tree crops. According to the 2007 National Survey of Pollution Sources in China, the total N loss from cropland was about 1 600 000 t, with 320 000 t attributed to surface runoff and more than 200 000 t caused by underground leaching; in comparison, the total phosphorus (TP) loss was much less, at about 108 000 t[3]. Field observations have been carried out to estimate the use of the major N fertilizers (urea, ammonium bicarbonate, and ammonium sulfate) in the production of major cereal crops (rice, wheat, and maize) in the major food-producing provinces in China. The total fertilizer N loss from crops to the environment in the 1990s was about 19.1%. Specifically, 5% of the fertilizer N entered the surface water by runoff, with 2% passed down to the groundwater by leaching, 1.1% released into the atmosphere through denitrification (N_2O), and 11% released through ammonia (NH_3) volatilization[4]. In addition, a eutrophication study in Dianchi Lake (Yunnan Province, China) reported that the total N (TN) generated by non-point source pollution comprised 44.5% of the total pollution load, while the TP comprised only 26.7% of the total pollution load[5].

To address the critical issue of non-point source pollution in agriculture, it is essential to implement soil management strategies that would reduce non-point source pollutant loads. Therefore, agricultural practices are increasingly being re-evaluated in China to prevent non-point source agricultural pollution, ameliorate the potential negative impacts, and protect the environment[2]. Such agricultural practices include soil testing and fertilizer recommendation, application of slow and controlled-release fertilizer, conservation tillage (e.g., no-till or minimum tillage), crop rotation, straw retention in the field, and combined organic and inorganic fertilizer application. In the account of irrational fertilization leads to nitrate N (NO_3-N) leaching, which is one of

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the major pathways of N loss in agricultural systems, including orchards. The leaching process not only reduces N-use efficiency but also causes NO_3-N accumulation in deep soil layers and groundwater pollution. In contrast, the vertical distribution of ammonium N (NH_4^+-N) decreases from the surface to the subsurface along the soil profile, indicating that NH_4^+-N migrates less than other N forms downward under the influence of soil adsorption[6,7]. Monitoring the distributions of different N forms in orchard soil profiles under fertilization could provide information that could facilitate sustainable fertilizer management.

Recently, concerns have emerged over water accessibility and N pollution, as well as the influence of agricultural practices on the environment, such as NO_3-N leaching due to irrational N fertilizer use[10-14]. Under efficient irrigation, improved water and N uptake by crops can minimize nutrient leaching[10]. In addition to reducing environmental pollution risk, proper application of irrigation water and N fertilizer have dual roles of increasing water and N productivity[15]. Therefore, the development of optimal water-N coupling management strategies that maximize N and water-use efficiencies is critical for environmental sustainability and agricultural productivity in humid regions[16].

Several studies have assessed the effects of N application on crop yield and soil nutrient balance[17-20]. Furthermore, supplemental irrigation coupled with N application considerably influences the final quality and characteristics of harvested cereals, in addition to influencing both post-harvest[19,20] and successive transformation processes[21-23]. However, little attention has been paid to N distribution and crop yield in arid regions under water-N coupling fertilization. Moreover, irrigation water availability is decreasing with increases in costs of operations and regulation of N usage. Therefore, there is a need to better understand how irrigation amounts interact with the N application rate in agricultural systems.

Weibei Dryland is the main apple-producing area in Shaanxi Province, China. In the rainfed region, excessive fertilization is a major source of concern[8]. In addition, the ecological environment is relatively fragile, with low and uneven precipitation, and poor soil moisture. All the factors above influence fruit yield and the economic benefits derived from apples as cash crops. In the rainfed agricultural area, the water supply for dryland crops is largely reliant on atmospheric precipitation. Drip irrigation (water-N coupling) is an effective method of increasing apple productivity and improving fruit quality for local fruit farmers. Drip irrigation can provide a favorable environment for crop growth and effectively improve water and nutrient-use efficiencies[9].

Therefore, in the present study, we hypothesized that supplemental drip irrigation coupled with N application would enhance N availability and apple yield, while minimizing N loss by leaching. The aim of the present study is to evaluate how different levels of drip irrigation (300-900 m^3/hm^2) and N application (0-600 kg/hm^2) influence soil N (TN, NO_3^--N, and NH_4^+-N) and apple yield in an orchard in Weibei Dryland. The results of the study could provide reference data for fertilizer management in apple orchards and facilitate sustainable development of the fruit production industry.

2 Materials and methods

2.1 Site description

Experiments were conducted for three consecutive years (2012-2014) in an apple orchard (109°55′18″E, 35°14′10″N) in Hanjing Town, Shaanxi Province, China. The local altitude is 850 m and the mean annual temperature is 10.5℃, with abundant light and large temperature differences between day and night. The mean annual precipitation is 519.9 mm, and the maximum evaporation is 1005.8 mm. The orchard area was 0.3 hm^2, mainly planted with dwarf Red Fuji (*Malus micromalus* Makino). The trees were eight years old and the row spacing was 3.0 m×2.5 m. The orchard soil was loess soil, and its basic physical and chemical properties before the experiment were summarized in Table 1.

Table 1 Basic properties of the apple orchard soil

Soil depth /cm	Total N /$g \cdot kg^{-1}$	Available N /$mg \cdot kg^{-1}$	Ammonium N /$mg \cdot kg^{-1}$	Nitrate N /$mg \cdot kg^{-1}$	Available P /$mg \cdot kg^{-1}$	Available K /$mg \cdot kg^{-1}$	Organic matter / $g \cdot kg^{-1}$
0-20	1.35	77.02	7.87	69.15	15.56	119.34	13.61
20-40	1.27	53.69	3.87	49.82	12.88	103.89	9.18
40-60	0.99	25.60	5.12	20.48	6.44	62.71	7.33
60-80	0.56	25.02	5.68	19.31	6.44	67.86	5.40
80-100	0.52	23.77	8.11	15.66	9.66	67.86	6.14

2.2 Experimental treatments

Apple trees with consistent growth and no evident pests or diseases were selected for the experiment. A total of 12 treatments were set up and each treatment had three replicates, with six trees per treatment. The treatments were arranged randomly. Three irrigation levels and four N levels were applied in the apple orchard (Table 2).

Urea (containing N: 46.7%) was applied as a basal dressing (30%) and three top dressings (70%, in the germination, fruiting, and fruit-bearing stages). For each application, the N fertilizer was dissolved in water and then dripped slowly into the soil around the root canopy. The drip holes were distributed within 0.5 m of the drip line on both sides of the canopy. In addition, triple superphosphate (containing P_2O_5: 46.1%) and potassium chloride (containing K_2O: 52.3%) were applied as basal fertilizers once quarterly along with N, at rates of 225 and 250 kg/hm^2, respectively. The other management practices were in accordance with the conventions of local farmers.

Table 2 Fertilizer application and drip irrigation levels of different treatments

Treatment	Nitrogen /$kg \cdot hm^{-2}$	Irrigation water /$m^3 \cdot hm^{-2}$	P_2O_5 /$kg \cdot hm^{-2}$	K_2O /$kg \cdot hm^{-2}$
N0W1	0	300	225	250
N0W2		600		
N0W3		900		
N1W1	200	300		
N1W2		600		
N1W3		900		
N2W1	400	300		
N2W2		600		
N2W3		900		
N3W1	600	300		
N3W2		600		
N3W3		900		

2.3 Sample analyses

Stratified soil sampling was conducted in the root zones of apple trees twice, namely, before the experiment (control) and post-harvest, after three consecutive years of experimentation. The sampling depth was 100 cm, and soil samples were collected at 20 cm intervals. After transportation to the laboratory, soil TN was determined using the semi-micro Kjeldahl method with a semi-automatic azotometer (Skalar San++, Netherlands). Soil NO_3^--N and NH_4^+-N were extracted with a 0.01 mol/L $CaCl_2$ solution and determined using a continuous flow injection analyzer (San++; Skalar, Netherlands).

Both soil available P and potassium (K) were leached with a mixture of 0.25 mol/L $NaHCO_3$ + 0.01 mol/L EDTA + 0.01 mol/L NH_4F. The P concentration in the extract was measured using the molybdenum blue colorimetric method, and the K concentration was analyzed by flame atomic absorption spectrometry. Soil organic matter was determined by potassium dichromate-concentrated sulfuric acid oxidation (external heating method) combined with ferrous sulfate titration[24].

The volumetric water contents of soil samples were measured by stratified sampling in April, May, June, August, September, and mid-October in the third year of the experiment. Water content measurements were carried out before and after oven-drying the samples at 105°C. By measuring the moisture content in the soil, the quality of dry soil, soil water volume, and soil total volume to obtain the mass water content and volume water content, the relationship between them could be found: Mass water content of soil = Volumetric water contents of soil × Soil bulk density.

2.4 Statistical analysis

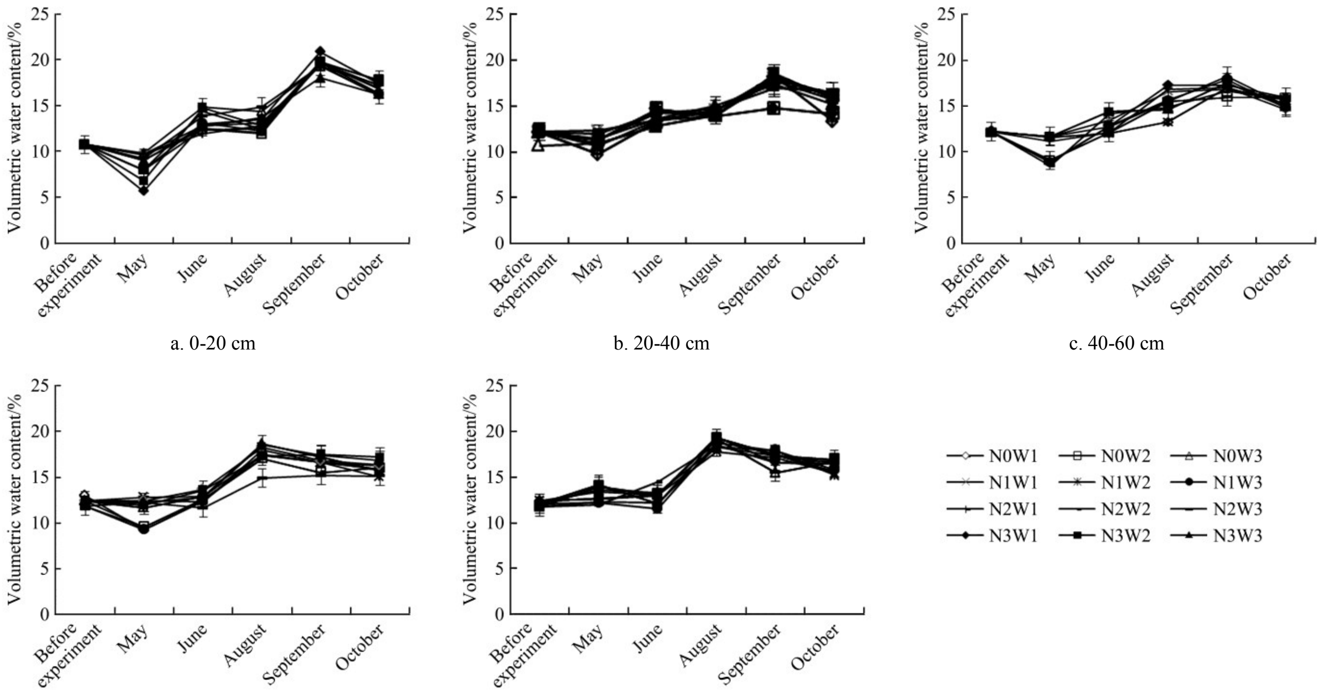
All the sample data were analyzed by a multi-way Analysis of Variance using a PROC GLM model of SAS (SAS Institute Inc., Cary, NC, USA) based on four sources of variation, namely: year (Y), irrigation (I), N (N), and depth (D). Significant differences in means of Y, I, N, and D were analyzed using the least significance difference test.

3 Results

3.1 Variation in volumetric water content in orchard soil profile

The volumetric water contents of each soil layer under different water-N coupling conditions were monitored continuously over the apple tree growth cycle from germination to fruit harvest. In the 0-100 cm soil profile, the overall soil water content trend revealed lower contents in the germination stage (May) than in the fruit enlargement stage (August-early September; Figure 1), and the minimum content of 5.644% in surface 0-20 cm (N3W1). Under different treatments, the soil water contents in the 0-20 cm layer were higher than those in the 20-100 cm soil layers and ranged from 8.53% to 20.8% throughout the apple growth cycle. The soil water contents of all treatments were especially higher in September than those of other stages. The soil water contents in the 0-20 cm surface layer basically represent the water characteristics of the orchard.

Due to four irrigation events, the lower soil layers maintained a water content in the 10%-18% range (Figure 1). Still, there were certain differences in soil water content among the irrigation treatments. For example, the values of the N0W3, N1W3, N2W3, and N3W3 treatments were slightly, but not significantly, higher than those of the other treatments throughout the apple growth cycle. However, there were no remarkable differences among the treatments from August to September. The 20-40 cm soil water content varied from 9.75% to 18.67% (Figure 1). This range of variation was slightly lower than that of the surface layer and even narrowed in the 40-100 cm soil layers.



a. 0-20 cm b. 20-40 cm c. 40-60 cm

d. 60-80 cm e. 80-100 cm

Figure 1 Continuous monitoring results of volumetric water content in the 0-100 cm orchard soil profile under different treatments (Treatment abbreviations are defined in Table 2)

3.2 Distribution of total nitrogen content in orchard soil profile

The TN contents in the 0-100 cm soil profile varied significantly under different levels of N application and drip irrigation (Figure 2). Under the no-N and irrigation-only treatments, the soil TN contents were lower than those under the other N-irrigation coupling treatments. Under no N application (N0W1, N0W2, and N0W3), the soil TN contents in the surface layers (0-40 cm) decreased from 1.35 g/kg before experiments to

<1.0 g/kg after treatments. The TN contents exhibited a decreasing trend with an increase in soil depth.

With an increase in the level of N applied, the TN contents of the soil profile changed dynamically. There was no significant difference in TN content in surface soil following the N1 treatment. However, due to the high-level irrigation in the N1W3 treatment, the TN content in the 20-80 cm soil layer in the N1W3 treatment was higher than those in the N1W1 and N1W2 treatments, and the maximum content was 2.34% at about 30 cm. After N2 application, soil TN content changed with an increase in soil depth, and was in the 1.0-20 g/kg range. Following N3 application, the TN content of surface soil ranged between 1.5 and 2.5 g/kg. In addition, the TN contents in the soil profile varied with an increase in irrigation. In the N3W2 and N3W3 treatments, higher TN content was observed in the 40-60 cm soil layer than in the same soil layer in other treatments, and the TN content in the 80-100 cm soil layer was greater than 1.2 g/kg, whereas that in the same soil layer of N3W3 treatment was 1.31 g/kg.

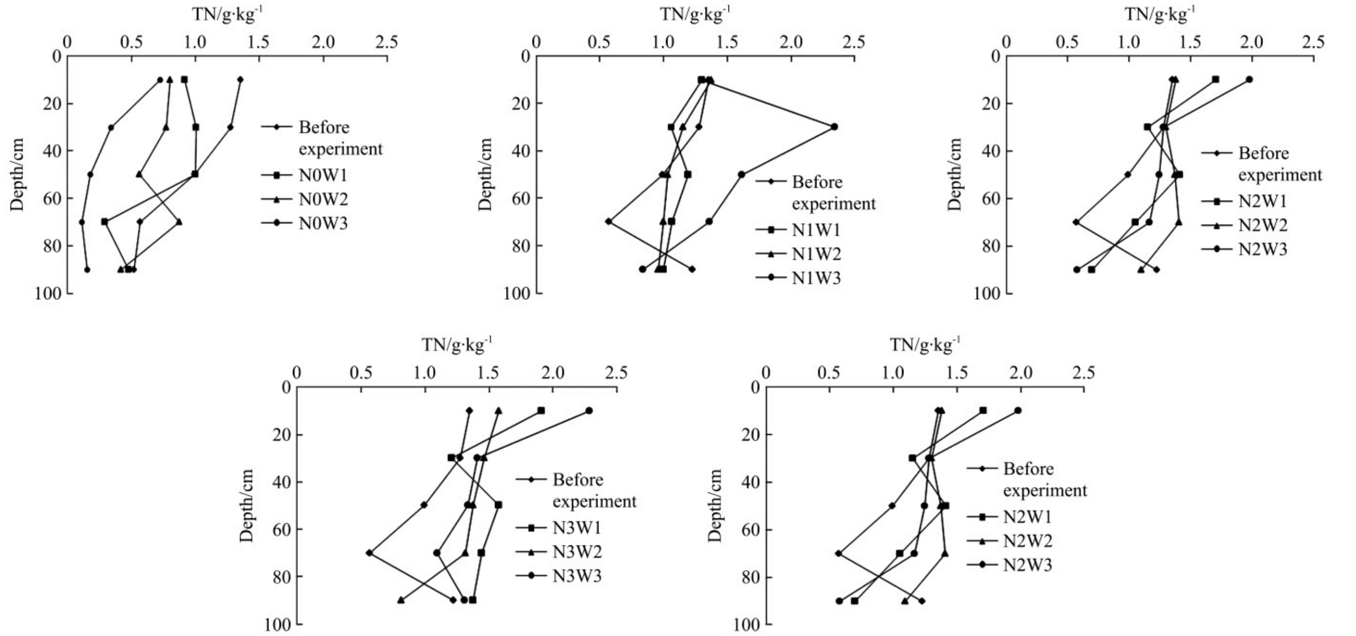


Figure 2 Distribution of total nitrogen (TN) content in the 0-100 cm orchard soil profile under different treatments
(Treatment abbreviations are defined in Table 2)

3.3 Distribution of available nitrogen content in orchard soil profile

NO_3^--N contents also varied markedly in the 0-100 cm soil profile under different fertilization treatments (Figure 3). Under no N application (N0W1, N0W2, and N0W3), NO_3^--N content did not change considerably, and was maintained at 40-65 mg/kg in the 0-20 cm soil layer. Furthermore, irrigation amount had minimal effect on NO_3^--N content. Generally, the NO_3^--N contents decreased with an increase in soil depth.

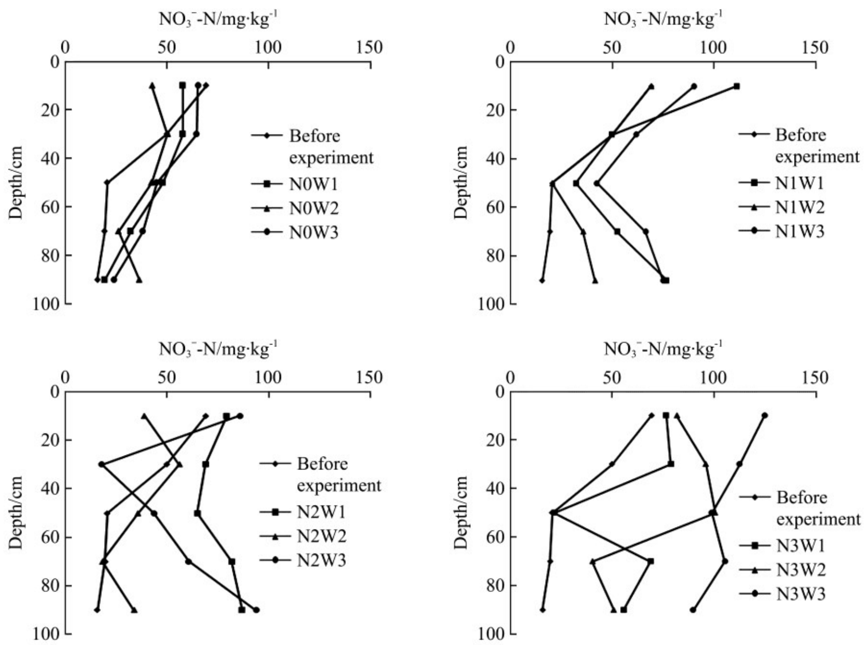


Figure 3 Distribution of nitrate nitrogen (NO_3^--N) content in the 0-100 cm soil profile under different treatments
(Treatment abbreviations are defined in Table 2)

Under low N (N1) treatments, the NO_3^--N content trends in the soil profile with an increase in irrigation amount were quite different from those in the no-N (N0) treatments. The NO_3^--N contents in the 0-20 cm soil layer were significantly higher than those of the no-N treatments and were in the 70-110 mg/kg range. The values first decreased with an increase in soil depth, and the lowest value was observed in the 40-60 cm soil layer. Below the 60 cm depth, the NO_3^--N contents began to increase toward the lower soil layers, and the increase was more pronounced under higher irrigation levels. Particularly, the NO_3^--N content in the 80-100 cm soil layer in the N1W3 treatment (74.9 mg/kg) was significantly higher than that before the experiment (15.66 mg/kg).

A continuous increase in N application rate led to greater variation in NO_3-N content in the soil profile. When the maximum levels of N application and drip irrigation were applied (N3W3), the NO_3^--N contents in different soil layers were the highest. The value was as high as 105.3 mg/kg in the 80-100 cm soil layer.

The distribution of NH_4^+-N content in the soil profile under different treatments is shown in Figure 4. In each soil layer, the NH_4^+-N contents of the N0 treatments were lower than those of the other treatments. The values were <10 mg/kg in all cases and exhibited a downward trend with an increase in soil depth.

Soil available N mainly includes two forms, NO_3^--N and NH_4^+-N. The percentages of NO_3^--N in soil available N were significantly higher than those of NH_4^+-N, and were maintained at >85% in the soil profile under different water-N coupling conditions (Table 3).

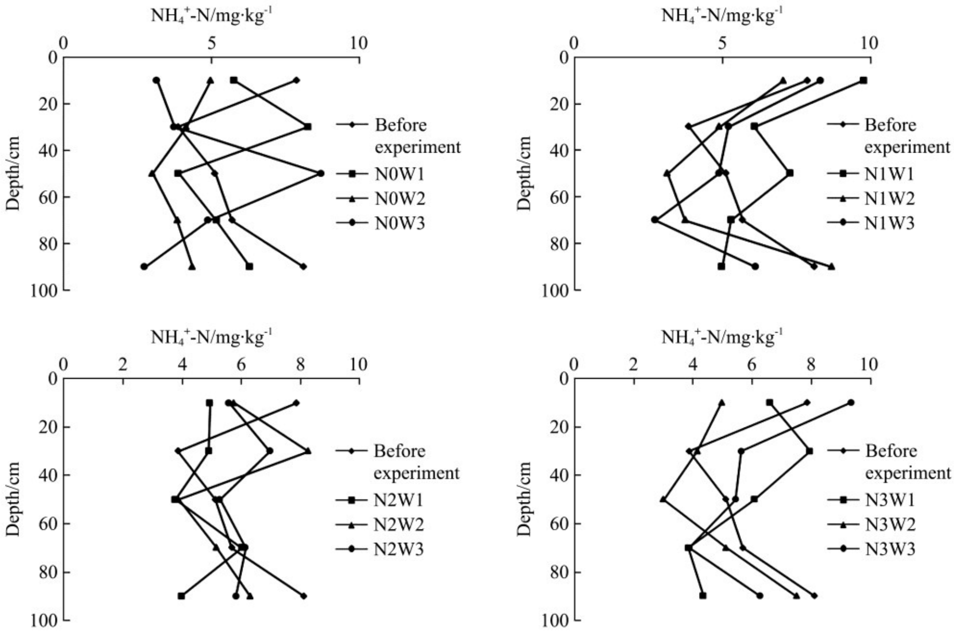


Figure 4 Distribution of ammonium nitrogen (NH_4^+-N) content in the 0-100 cm orchard soil profile under different treatments (Treatment abbreviations are defined in Table 2)

Table 3 Percentages of NO_3^--N to available nitrogen in the 0-100 cm soil profile under different treatments

Soil depth/cm	Ratios of NO_3^--N to available nitrogen/%											
	N0W1	N0W2	N0W3	N1W1	N1W2	N1W3	N2W1	N2W2	N2W3	N3W1	N3W2	N3W3
0-20	90.9	89.5	95.4	91.9	90.7	91.6	94.1	87.1	93.9	92.1	94.3	93.0
20-40	87.5	92.4	94.5	89.1	91.1	92.2	93.3	87.1	72.0	90.8	95.8	95.2
40-60	92.5	93.4	83.8	81.5	86.7	89.7	94.5	90.2	89.2	78.0	97.1	94.8
60-80	86.1	87.1	88.6	90.8	90.5	96.0	93.2	77.9	90.8	94.7	88.7	96.5
80-100	75.3	89.3	89.6	93.9	82.7	92.4	95.6	84.2	94.2	92.7	87.1	93.5

Note: Treatment abbreviations are defined in Table 2

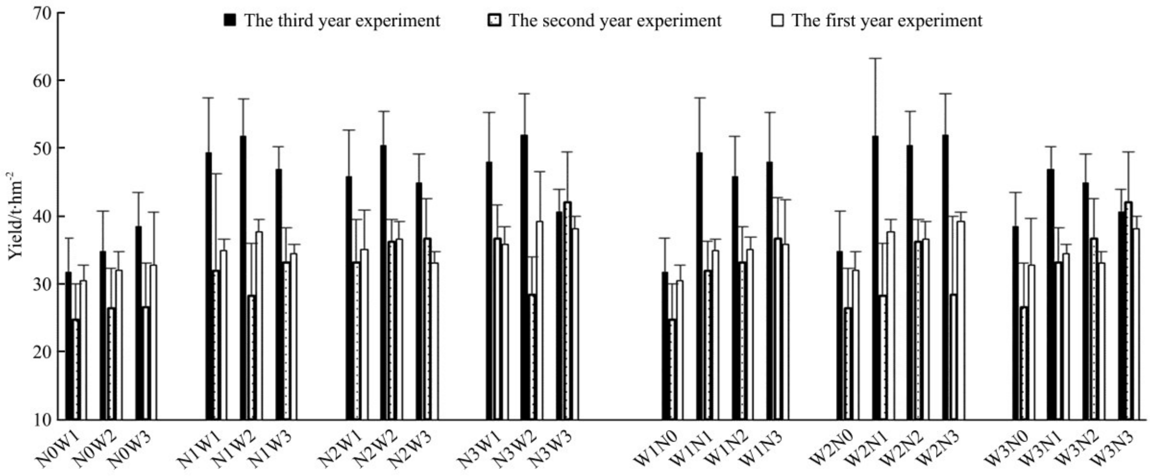
3.4 Effects of water-nitrogen coupling fertilization on apple yield

The effects of different fertilization treatments on apple yield over three consecutive years are shown in Figure 5. Apple yield increased significantly under favorable water-N coupling fertilization conditions. It was controlled by two factors, namely N application rate and drip irrigation amount. Under similar N application levels, such as N0, apple yield in the N0W1 treatment was significantly lower than those in the N0W2 and N0W3 treatments, with the lowest value observed in the second year of the experiment, at 24.7 t/hm^2 (Figure 5). This yield difference was more pronounced with an increase in the number of years, and was 6.7 t/hm^2 between the N0W1 and N0W3 treatments in the third year. In addition, under the same treatments, apple yields in the second year were lower than the yields in other years.

When low-N was applied, apple yield in the N1W2 treatment was higher than those of the N1W1 and N1W3 treatments. Similar trends were observed under moderate- and high-N treatments. That is, the yields of the N2W2 and N3W2 treatments were higher than those of the N2W1/N2W3 and N3W1/N3W3 treatments, respectively. Furthermore, there were certain differences across different years. Generally, similar trends were observed in the first and third years; however, apple yield in the third year was higher than that in other years. The mean yield of all treatments in the third year was as high as 45.9 t/hm^2, while the mean yields in the first and second years were 35.4 t/hm^2 and 32.8 t/hm^2, respectively.

When irrigation was controlled at the same level, such as in

W1, apple yields in the N2W1 and N3W1 treatments were higher than those in the N1W1 and N0W1 treatments. Regardless of the irrigation amount, the lowest yield was obtained under no-N application treatments. In the third year, apple yields under the W2 treatments were significantly higher than those under the W3 and W1 treatments.



Note: Treatment abbreviations are defined in Table 2

Figure 5 Apple yield under different fertilization treatments

3.5 Effects of water-nitrogen coupling fertilization on orchard economic benefits

The economic benefits of apples under water-N coupling fertilization in the orchard in Weibei Dryland are summarized in Table 4. Different fertilization treatments increased mean apple yield by 7.3%-41.62%. The yield in the N2W2 treatment was as high as 41.01 t/hm^2, which was 41.62% higher than that in the N0W1 treatment. In addition, apple yields in the N3W1 and N3W2 treatments were 38.50% and 36.65% higher, respectively, than those in the N0W1 treatment. The N3W3 treatment received the highest amounts of N fertilizer and irrigation water; however, the associated yield increase was not high, at only 28.68%. Considering the water and fertilizer input in the N3W3 treatment being the highest (75 000 RMB yuan/hm^2), the associated net income was relatively low.

The results of the economic benefit analysis showed that the output value of the N2W2 treatment was 237 900 Yuan/hm^2, and the associated net income was 232 000 Yuan/hm^2, which was a net increase of 67 200 Yuan/hm^2 when compared with that of the N0W1 treatment. The output value of the N3W1 treatment was second only to that of the N2W2 treatment, and its net income, 226 600 Yuan/hm^2, was slightly higher than those of other treatments. Although the N0 treatment received no N fertilizer input, its apple yield was relatively low, so the associated net income was the lowest. The yield difference in the N1 treatments under different irrigation levels was not significant. However, the N1W3 treatment received a high amount of water, so the output value was lower than those of the N1W1 and N1W2 treatments.

Table 4 Economic benefits of apple in the orchard in Weibei Dryland

Treatment		Mean apple yield/t·hm^{-2}	Percentage increase/%	Mean output value /10^4 Yuan·hm^{-2}	Fertilization investment /10^4 Yuan·hm^{-2}	Net income /10^4 Yuan·hm^{-2}
N0	W1	28.96^c	--	16.80	0.32	16.48
	W2	31.08^c	7.30	18.02	0.39	17.63
	W3	32.58^c	12.48	18.89	0.47	18.43
N1	W1	38.71^b	33.68	22.45	0.41	22.04
	W2	39.27^b	35.61	22.78	0.49	22.29
	W3	38.14^b	31.69	22.12	0.56	21.56
N2	W1	38.91^b	34.37	22.57	0.51	22.06
	W2	41.01^a	41.62	23.79	0.58	23.20
	W3	38.20^b	31.90	22.15	0.66	21.50
N3	W1	40.11^a	38.50	23.26	0.61	22.66
	W2	39.58^a	36.65	22.95	0.68	22.27
	W3	37.27^b	28.68	21.61	0.75	20.86

Note: Treatment abbreviations are defined in Table 2. Apple price: 5.8 RMB yuan/kg; fertilizer price: 4.78, 4.17, and 7.0 RMB yuan/kg for N, P_2O_5, and K_2O, respectively; agricultural water charge: 3.0 RMB yuan/t; and the cost-benefit analysis did not include other costs except for fertilizer. Different letters in the same column mean significant difference at the 0.05 level.

4 Discussion

Water-N coupling management has prominent effects on crop yields, soil N reserves, and nitrate leaching[29]. The optimal water-N coupling management strategy can not only meet the needs of crop growth but also effectively maintain the N reserves of arable land and reduce groundwater pollution caused by nitrate leaching. Therefore, the present study tested 12 water-N coupling fertilization treatments in an apple orchard in the Weibei Dryland. In all cases, the three N forms (TN, NO_3^--N, and NH_4^+-N) occurred at considerably high levels in the surface layer than in the lower soil layers. In each soil layer, the contents of different N forms were ranked as follows: TN > NO_3^--N > NH_4^+-N. N application increased total and available N significantly in the 0-20 cm soil layer. However, extremely high irrigation levels could cause soil nitrate leaching.

According to the classification criteria proposed by Zhang et al.[25], the TN content of orchard soil can be divided into three levels: TN>1.0 g/kg, which represents TN-rich soil; TN= 0.75-1.0 g/kg, which represents soil with a moderate TN level; and TN<0.75 g/kg, which represents a TN-deficient soil. Here, we observed that soil TN contents generally decreased after irrigation-only treatments, when compared with the levels before experimentation. Soil conditions changed from TN-rich levels to moderate TN or TN-deficient levels because fruit trees absorbed and transported high N amounts from the surface soil to the above-ground plant parts during growth. However, soil TN content in the surface soil varied in the 1.5-2.5 g/kg (TN-rich) range under the N3 treatments, and the values of different soil layers changed dynamically with an increase in irrigation amount. In particular, the N3W2 and N3W3 treatments led to TN contents in the 40-60 cm soil layer higher than those in other treatments, and the TN content in the 80-100 cm soil layer exceeded 1.2 g/kg.

NO_3^--N contents generally decreased with an increase in soil depth under the irrigation-only treatments. During the growth of fruit trees, root activity was improved and soil NO_3^--N was enhanced to meet the increased biomass requirements for shoot growth and fruit expansion. Therefore, the translocation of NO_3^--N to the above-ground parts was promoted, which in turn reduced soil NO_3^--N content under the no N fertilization treatments. Following N application (e.g., N1), the lowest NO_3^--N contents were observed in the 40-60 cm soil layer, which corresponded with the fruit tree root distribution at the depth[26]. In addition, NO_3^--N content tended to increase toward greater soil depths, > 60 cm depth, especially under irrigation. The main reason is that the root system cannot reach the deeper soil layers, while excessive irrigation causes nitrate leaching.

The highest NO_3^--N content in each layer of the 0-100 cm soil profile was observed under the N3W3 treatment, which received the highest water and fertilizer amounts. Especially in the 80-100 cm soil layer, the NO_3^--N content in the N3W3 treatment reached 105.3 mg/kg. The result is consistent with the finding of Zhang et al.[30], which showed that severe nitrate leaching occurred in the soil when the N application rate exceeded 500 kg/hm^2. In addition, Kou et al.[31] found that when the N surplus exceeded 500 kg/hm^2 in an orchard (Huimin, Shandong Province, China), soil NO_3^--N accumulation increased with an increase in soil depth, and up to 60% of the accumulation occurred in the 90-180 cm soil layer (mean = 976 kg/hm^2). In the present study, the N application level of the N3 treatments was 600 kg/hm^2 (>500 kg/hm^2). Taking into account the high irrigation level, the NO_3^--N accumulation levels in different soil layers can be substantial.

The vertical NH_4^+-N content distribution was characterized by the accumulation in the surface layers and depletion in the lower layers. The distribution trend indicates that NH_4^+-N migrated less downward due to soil adsorption, which is consistent with the results of Lu et al.[27]. However, NH_4^+-N only accounted for a low percentage (<15%) of the soil available N in the present study, which is consistent with the findings of Ran et al.[28] in the Weibei Dryland. Indeed, the main form of inorganic N occurring in soil and lost by leaching is NO_3^--N. Under dry conditions, nitrification results in NO_3^--N accumulation, while irrigation or rainfall promotes the downward migration of NO_3^--N[27]. NO_3^--N leaching in orchard soil due to excessive fertilizer and water is a major soil N loss pathway, which not only reduces N fertilizer-use efficiency in orchards but also causes NO_3^--N accumulation in deep soil layers and groundwater pollution.

Zhang et al.[32] reported that soil moisture is a carrier of N leachate and precipitation and irrigation influence leaching levels. In the present study, the surface soil water content was maintained between 8.53% and 20.8% across different treatments. Higher values were observed in September, which was not only linked to the rainy season but also to supplemental drip irrigation. Generally, soil water content tended to increase with an increase in irrigation level. However, similar values were observed in lower soil layers from August to September, mainly because the amount of rainwater at that stage was greater than the amount of irrigation water applied, which minimized the difference in soil water content. Furthermore, the soil water content varied over a smaller range in the lower soil layers compared to the surface soil layer, under different irrigation levels, mainly due to the influence of climatic conditions and evaporation on the surface soil. Because the water contents of lower soil layers guarantee water supply to root systems, the results indicate that appropriate drip irrigation can maintain soil water content and thereby promote production in fruit trees in the apple orchards in drylands, which is a prerequisite for high fruit yield in the Weibei Dryland.

According to Sun et al.[36], rational fertilization through drip irrigation can improve water-use efficiency in drylands, thereby facilitating crop yield increases. Irrigation also regulates fertilizer effects, and water can improve fertilizer-use efficiency. In the present study, the apple yields under the irrigation-only treatments were lower in the second year when compared with other years, mainly because of the “cold spring” in the second year, which caused forest damage over an area of 1733 hm^2 in Shaanxi Province. Following N application, the highest apple yield was obtained under medium irrigation levels. Either too high or low levels of irrigation are not conducive to apple production. The effects of water and fertilizer management became more evident with the prolongation of field experiments in orchards.

Zhang and Shan[37] demonstrated that N as a nutrient can enhance crop sensitivity to drought, and greatly reduces crop relative water content, water potential, and transpiration loss; additional N benefits include an increase in free water content, decreases in irreducible water content and membrane stability, and improvement in water-use efficiency. Under similar irrigation levels, in the present study, the lowest yield was obtained under no-N application, indicating that N application rate was the major reason for the increase in fruit yield. In addition, irrigation water can maximize the effects of N fertilizer, thereby enhancing fruit yield to a great extent. However, in the third study year, we observed that apple yield under moderate irrigation was higher than those under low or high irrigation levels. A plausible reason is that high-level irrigation leads to N migration with water infiltration, causing N fertilizer loss.

Excessive fertilization and irrigation would inevitably lead to soil NO_3^--N leaching and subsequent accumulation in the deep soil layers outside the root zone. This fraction of NO_3^--N is not easily absorbed or utilized by plants, which results not only in fertilizer waste but also in soil and groundwater pollution. “Underground fertile water,” which refers to groundwater containing high concentrations of nitrate, has emerged in some areas of China with intensive agricultural production[33,34]. Soil water and nutrients are the most basic materials required for the growth and development of fruit trees. Only when they are integrated and co-exist in the orchard soil can they have positive effects on crop growth and yield through interactive effects[35]. It is vital to adjust the levels of irrigation and fertilizer application within reasonable ranges based on local conditions to achieve a synergy between water and fertilizer and "enhance fertilizer effects with water" and "regulate water availability with fertilizer", which are of great significance for environmental protection in terms of conservation of water and fertilizer resources.

5 Conclusions

Different water-N coupling treatments influenced the distribution of soil N (TN, NO_3^--N, and NH_4^+-N) in the 0-100 cm soil profile of an apple orchard in Weibei Dryland. NO_3^--N content decreased toward lower soil layers gradually, and the lowest values were observed in the 40-60 cm layer. NO_3^--N content exhibited dynamic changes with an increase in N application level, and the highest value of each soil layer was observed under high-N and high-irrigation levels (N3W3 treatment). However, the NH_4^+-N content was relatively low (<10 mg/kg) and exhibited a downward trend with an increase in soil depth. Different water-N coupling treatments also increased apple yield when compared with the yield under drip irrigation only (N0W1 treatment), and the highest yield was observed under the medium-N and medium-irrigation levels (N2W2 treatment). Considering apple yield and potential economic and environmental benefits, the N2W2 treatment (N=400 kg/hm^2, drip irrigation = 600 m^3/hm^2) is the optimal strategy for water-fertilizer coupling drip irrigation in the apple orchard in Weibei Dryland.

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[References]

[1] Issaka F, Zhang Z, Zhao Z Q, Asenso E, Li J H, Li Y T, et al. Sustainable conservation tillage improves soil nutrients and reduces nitrogen and phosphorous losses in maize farmland in Southern China. Sustainability, 2019; 11(8): 2397. doi: 10.3390/su11082397.

[2] Luo L G, Qin L H, Wang Y, Wang Q. Environmentally-friendly agricultural practices and their acceptance by smallholder farmers in China—A case study in Xinxiang County, Henan Province. Sci Total Environ, 2016; 571: 737–743.

[3] Ministry of Environmental Protection of the People's Republic of China (MEP). National Bureau of Statistics of the People's Republic of China (NBS); Ministry of Agriculture of the People's Republic of China (MOA). The First National Survey of Pollution Sources Bulletin, 2010. (in Chinese)

[4] Zhu Z L, Chen D L. Nitrogen fertilizer use in China—Contributions to food production, impacts on the environment and best management strategies. Nutr Cyc Agroecosystem, 2002; 63: 117–127.

[5] Shen Z Y, Liao Q, Hong Q, Gong Y W. An overview of research on agricultural non-point source pollution modelling in China. Sep. Purif Technol, 2012; 84: 104–111.

[6] Fan J, Shao M G, Hao M D, Wang Q J. Desiccation and nitrate accumulation of apple orchard soil on the Weibei dryland. Chinese Journal of Applied Ecology, 2004; 7: 1213–1216. (in Chinese)

[7] Peng F, Jun L, Zhang L N, Yu C, Kasimu J. Soil nitrogen contents and deep profile distributions in apple orchards of the Loess Plateau. Journal of Plant Nutrition and Fertilizers, 2013; 19(2): 420–429.

[8] Zhao Z P, Duan M, Yan S, Liu Z F, Wang Q, Fu J, et al. Effects of different fertilizations on fruit quality, yield and soil fertility in field-grown kiwifruit orchard. Int J Agric & Biol Eng, 2017; 10(2): 163–172.

[9] Li J S, Zhang J J. Nitrogen distributions in soil under fertigation from a point source. Transactions of the CSAE, 2002; 18(5): 61–62.

[10] Sigua G C, Stone K C, Bauer P J, Szogi A A. Efficacy of supplemental irrigation and nitrogen management on enhancing nitrogen availability and urease activity in soils with sorghum production. Sustainability 2020; 12: 8358. doi: 10.3390/SU12208358.

[11] Sigua G C, Stone K C, Bauer P J, Szogi A A. Biomass and nitrogen-use efficiency of grain sorghum with nitrogen and supplemental irrigation. Agron J, 2018; 110: 1119–1127.

[12] Gholamhoseini M, Alikhani M A, Sanavy S A M, Mirlafiti S M. Interaction of irrigation, weed and nitrogen on corn yield, nitrogen use efficiency and nitrate leaching. Agric Water Manag, 2013; 126: 9–18.

[13] Li X, Hu C, Delgado J A, Zhang Y, Ouyang Z. Increase nitrogen use efficiency as a key mitigation alternative to reduce nitrate leaching in north China plain. Agric. Water Manag, 2007; 89: 137–147.

[14] Fang Q, Yu E, Wang Y, Chen G, Zhang J, Wang J, Li L. Soil nitrate accumulation, leaching and crop nitrogen use as influenced by fertilization and irrigation in an intensive wheat-maize double cropping system in the North China Plain. Plant Soil, 2006; 284: 335–350.

[15] Katterer T, Hansson A C, Andren O. Wheat root biomass and nitrogen dynamics-effects of daily irrigation and fertilization. Plant Soil, 1993; 151: 21–30.

[16] Zougmore R, Mando A L, Stroosnijder S. Effect of soil and water conservation and nutrient management on the soil-plant water balance in semi-arid Burkina Faso. Agric Water Manag, 2004; 65: 103–120.

[17] McDonald R I, Girvetz E H. Two challenges of U.S. irrigation due to climate change: Increasing irrigated area in wet states and increasing irrigation rates in dry states. PLoS One, 2013; 8(6): e65589. doi: 10.1371/journal.pone.0065589.

[18] Stone K C, Sigua G C, Bauer P J. Supplemental irrigation for grain sorghum production in the US eastern coastal plain. Appl Eng Agric, 2018; 34: 395–402.

[19] Liu X J, Ju X T, Zhang F S. Nitrogen dynamics and budgets in a winter-maize cropping system in the North China Plain. Field Crop Res, 2003; 83: 111–124.

[20] Cappelli A, Guerrini L, Parenti A, Palladino G, Cini E. Effects of wheat tempering and stone rotational speed on particle size, dough rheology and bread characteristics for a stone-milled weak flour. J Cereal Sci, 2020; 91: 102879. doi: 10.1016/j.jcs.2019.102879.

[21] Cappelli A, Oliva N, Cini E. Stone milling versus roller milling: A systematic review of the effects on wheat flour quality, dough rheology, and bread characteristics. Trends Food Sci Technol, 2020; 97: 147–155.

[22] Cappelli A, Bettaccini L, Cini E. The kneading process: A systematic review of the effects on dough rheology and resulting bread characteristics, including improvement strategies. Trends Food Sci Technol, 2020; 104: 91–101.

[23] Cappelli A, Guerrini L, Cini E, Parenti A. Improving whole wheat dough tenacity and extensibility: A new kneading process. J Cereal Sci, 2019; 90: 102852. doi: 10.1016/j.jcs.2019.102852.

[24] Bao S D. Soil and agriochemstry analysis science. 3rd Eds. Beijing: China Agriculture Press, 2000; pp.302– 316. (in Chinese).

[25] Jin Z, Wu F Q, Yang Z, Min X. Survey and evaluation of soil nutrients in the apple production regions in Weibei Highland. Acta Agriculturae Boreali-occidentalis Sinica, 2011; 20(1): 102–108.

[26] Jian W, Tong Y A. Study on absorption, utilization and storage of nitrogen of kiwifruit tree. Journal of Plant Nutrition and Fertilizers, 2008; 14(6): 1170–1177.

[27] Yuan L, Dang T H, Qi C. Distribution characteristics of soil moisture and mineral nitrogen in soil profile of apple orchard in gully region of loess plateau. Journal of Soil and Water Conservation, 2021; 35(2): 106–112.

[28] Ran W, Xie Y S, Hao M D. Study on accumulation and distribution of soil mineral nitrogen in apple orchard in Weibei Dryland, Agricultural Research in the Arid Areas, 2008; 26(3): 157–160.

[29] Lin C, Zhang J B, Zhao B Z, Ping H. Dynamics of nitrogen in topsoil related to integrated water and nitrogen management. Acta Pedologica Sinica, 2013; 50(3): 459–468.

[30] Zhang W L, Wu S X, Ji H J, Kolbe H Z. Estimation of agricultural non-point source pollution in China and the alleviating strategies. Scientia Agricultura Sinica, 2004; 37(7): 1008–1017.

[31] Kou C L, Ju X T, Zhang F S. Nitrogen balance and its effects on nitrate-N concentration of groundwater in three intensive cropping systems of North China. Chinese Journal of Applied Ecology, 2005, 16(4): 660–667. (in Chinese)

[32] Zhang J B, Yi C, Cai Z C. The mechanisms of soil regulating nitrogen dynamics. Advances in Earth Science, 2019; 34(1): 11–19.
[33] Ju X T, Zhang F S. The accumulation of soil nitrate nitrogen in northern China and its environmental impact. Ecological Environment, 2003; 12(1): 24–28.
[34] Lu H Y, Hu Z Y, Zhang R J, Pang Y W, Yin X F, Wu Y H. Spatial variability of nitrogen in soils in farmland adjacent suburban villages at northern bank of Dianchi Lake. Journal of Agro-Environment Science, 2010; 29(8): 1618–1623.
[35] Xia S, Chai Z P, Jiang P A. Effects of water and nitrogen coupling on quality of red Fuji Apple under drop irrigation condition in the south of Xinjiang. Journal of Nuclear Agricultural Sciences, 2011; 25(5): 1042–1046. (in Chinese)
[36] Sun W T, Sun Z X, Wang C X, Liang G. Coupling effect of water and fertilizer on corn yield under drip fertigation. Scientia Agricultura Sinica, 2006; 39(3): 563–568.
[37] Lei W, Zhang F C, Zou H Y, Lu J S, Guo J J, Xue Z Q. Effect of water deficit and nitrogen rate on the growth, water and nitrogen use of spring wheat. Journal of Triticeae Crops, 2019; 39(4): 478–486.
[38] Hamouda Y A, Guo X P, Wang Z C, Shaghaleh H, Hassan S C A, Bakour A. Effects of irrigation regime and soil clay content and their interaction on the biological yield, nitrogen uptake and nitrogen-use efficiency of rice grown in southern China. Agricultura Water Management, 2019; 213: 934–946.