THE COUPLING EFFECT OF WATER AND NITROGEN TO THE WATER AND NITROGEN USE EFFICIENCY AND YIELD OF SOYBEAN UNDER DRIP IRRIGATION MODE

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Abstract. The soybean in China northeastern black soil has low yield, low use efficiency of water and fertilizer, which has overly high amount of nitrogen residual. Three different drip irrigation mode amount (300 mm, 350 mm, and 400 mm) and five different amount of nitrogen was designed in this paper to study the influence of water and nitrogen controlling to the water and fertilizer use efficiency and the amount of nitrogen residual under drip irrigation mode. According to our experiment results, the water consumption of soybean increased with the growth of drip irrigation mode amount, and in all treatment, soybean consumed the most amount of water at seed filling period. There is no significant difference in water consumption amount between each treatment during seedling period, but there were significant differences in the water consumption of soybean at branching period, flowering and pod period, and seed filling period. Nitrogen fertilizer alone does not have significant influence on soybean water, but the interaction between nitrogen fertilizer and soybean had significant difference in water consumption amount. The yield reached the biggest amount of 3250 kg/hm^2 when nitrogen drip amount was 400 mm, and nitrogen application rate was 81 kg/hm^2. The yield increased with the growth of irrigation amount, but the yield increase rate became slow. When the nitrogen application amount was at a low level, there was a positive interaction between water and nitrogen, which showed a synergistic acceleration effect. When the nitrogen application rate was at a high level, there was a negative interaction between water and nitrogen. When the drip irrigation mode amount was 350 mm and the nitrogen application rate was 81 kg/hm^2, the WUE was the highest, which was 0.60 kg/m^3. In a certain range of nitrogen application, increasing irrigation amount can promote WUE, while the amount was over a certain range, WUE decreased. After harvest, the amount of nitrate nitrogen residual in the 0–100 cm soil varied greatly among different nitrogen fertilizer treatments, and the nitrogen fertilizer application amount was greater, the nitrogen residual was greater. In the W3N3 treatment which has the highest yield, the yield was at 42 kg/hm^2 less than the W3N4 treatment at the highest amount of nitrate nitrogen residual, which is a reduction of 35.78%. The results showed that proper combination of water and nitrogen application could reduce nitrogen residual in soil after harvest. The research results can provide theoretical basis and technical support for the efficient utilization of water and fertilizer resources in the black soil region located in northeastern China.

Keywords: *Heilongjiang Jiusan Management Bureau, irrigation and fertilization, water consumption, harvest yield; nitrogen utilization*

Introduction

Irrigation and nitrogen application are the two important factors affecting soybean yield. Due to frequent spring droughts and excessive application of nitrogen fertilizer in the western part of Northeast China, water and fertilizer utilization rates in this region are low and nitrogen residual are too high (Zou et al., 2012; Wang et al., 2016). In recent years, the soybean planting area in the northeast black soil area has grown rapidly, and the soybean planting area in Heilongjiang province alone has reached more than 60 million mu. The soybean planting area in the west of Heilongjiang Province is known as “nine spring drought out of ten years”, spring drought occurs year after year and the surface water of Songnen Plain has reached the mining red line. Drip irrigation mode, as an efficient water-saving irrigation technology, has the advantages of small irrigation quota, high utilization efficiency of irrigation water and easy automatic control, etc., has widely used in many countries around the world (especially in arid and semi-arid areas) (Qi and Pang, 2000; Tao et al., 2013).

Meanwhile, due to traditional planting habits, most farmers are also used to applying chemical nitrogen fertilizer in large quantities. Excessive application of nitrogen fertilizer not only increases costs, but also causes excessive soil residual (Hao et al., 2019). Therefore, studying coupling effect of different drip irrigation mode and the reduction of nitrogen fertilizer to soybean plays a significant role in improving water and nitrogen utilization efficiency and increasing yield, both scientifically saving water and stabilizing and even increasing yield, carrying out water nitrogen fertilizer management strategy. Moreover, it can also provide technological support to realize strategic target of “one control, two reduction, three solving,” which means firstly the total amount of water used in agriculture industry should be controlled. Secondly, the amount of fertilizer and pesticides should be reduced. Thirdly, the pollution caused by livestock, poultry, plastic film mulching, and waste straw burning should be solved by recycling.

Water is the main playing factor in the production of soybean. The soybean needs 600–800 g of water to form 1 g of dry matter, and 2 kg of water is consumed to produce 1 kg of soybean seeds (Hicks et al., 1984). Studies show that within a certain range of water (300–700 mm), the yield increases significantly with the growth of water consumption. There was a significant positive correlation between two variables (Wang and Wang, 1995; Wang et al., 2014; Fu and Zhang, 2009; Xia et al., 2014). Appropriate fertilization can effectively inhibit inter-tree soil evaporation and improve water use efficiency (Huang et al., 2016). In areas with insufficient irrigation, fertilization can improve soil water storage efficiency (Wang et al., 2016). Appropriate nitrogen fertilizer can improve yield, but excessive nitrogen fertilizer input will lead to insignificant or even reduced yield growth (Xia and Gong, 2017). Although soybean has the function of nitrogen fixation, its own nitrogen fixation function cannot meet the needs of soybean growth. At the early stage of soybean growth, root nodules gradually form, which cannot meet the demand for nitrogen of soybean, so nitrogen fertilizer should be applied (Duan et al., 2007). In recent years, with the growth of fertilizer application, it has directly or indirectly caused serious harm to the environment (Du et al., 2009; Yan et al., 2011). Nitrogen utilization rate in China is about 30%–35%, which is relatively low (Zhang et al., 2008). Therefore, rational fertilization is very important for growing soybean, protecting farmsoil, and water environment (Xuan, n.d.).

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Therefore, soybean in northeast black soil region was studied by using nitrogen and water factor experiment to find the best combination of water and nitrogen application, which would provide some technical support and theoretical basis for improving crop yield, water and fertilizer utilization and controlling environmental pollution caused by fertilization.

Materials and methods

Test site and basic information

The experiment was conducted in Heshan Farm Science and Technology Park, Heihe City, Heilongjiang Province (48°43'~49°03' N, 124°56'~126°21'E). The average annual temperature in the test area was ≥ 10℃, the annual effective accumulated temperature was 2000℃–2300℃, and the frost-free period was 115–120 d, belonging to the cold temperate continental climate, and the rainy season was mostly concentrated in summer. The average annual precipitation ranges from 450 to 500 mm. Precipitation during soybean growth period ranges from 300 to 330 mm. The local soil type is mainly black soil, and the cultivated soil is weakly acidic. The basic physical and chemical properties of 0–20 cm soil layer in the test site are as follows. The soil bulk density was 1.21 g/cm^3, alkali-hydrolyzable nitrogen was 137.8 mg/kg. Rapidly available phosphorus was 20.35 mg/kg, rapidly available potassium was 180.16 mg/kg, and organic matter was 22.1 g/kg and PH was 6.26.

Experimental design

Layout of the test site

The crop planted is soybean, and the tested specie is Heihe 43, the main local variety (provided by Beidahuang Seed Company). The tested fertilizers were urea (N = 46%), potassium (the content of K2O is 60%) and diamine (the content of P2O5 is 16%). The planting method was "one ridge, single tube and double row," the ridge height was 0.2 m, the ridge width was 0.4 m, the ditch bottom width was 0.4 m, the ridge spacing was 1 m, two rows of soybean were planted on the ridge, and the seedling number was 360, 000 plants/hm^2. Drip irrigation mode belt was laid in the middle of the ridge, the flow rate of the drip head was 1.38 L/h. The distance between the drip heads was 0.3 m, and the area of each test plot was 10 m × 10 m = 100 m^2. Sowing on April 25th and harvesting on September 25th. The test layout was shown in *Figure 1.*

Field plot experiment design

In this experiment, soybean varieties, densities, pesticide application and other technologies used were the same, three different drip irrigation mode amount is set up in the experiment, the respective amount is 300 mm, 350 mm, 400 mm, and the situation of no irrigation was used as control. The drip irrigation mode amount ratio during each growth period was 1.5:1.5:5:2 in seedling stage, branching stage, flowering stage, seed filling stage respectively. According to local soil conditions and previous research. Five different nitrogen application rates were set as follows. Conventional nitrogen application level is at 90 kg/hm^2, nitrogen reduction level of 10% was at 81 kg/hm^2, nitrogen reduction level of 20% is at 72 kg/hm^2, nitrogen reduction level of 30% is at 63 kg/hm^2. Fertilization ratio of base fertilizer: top fertilizer (applied with water drops at

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flowering and seed filling stage) = 2:1. Potassium fertilizer (30 kg/hm^2) and phosphate fertilizer (150 kg/hm^2) were applied all at once as base fertilizer. A total of 16 treatments were used in the comprehensive experimental design method. Each treatment was repeated for 3 times, and a total of 48 test cells were randomly arranged. The experimental design was shown in *Table 1*.

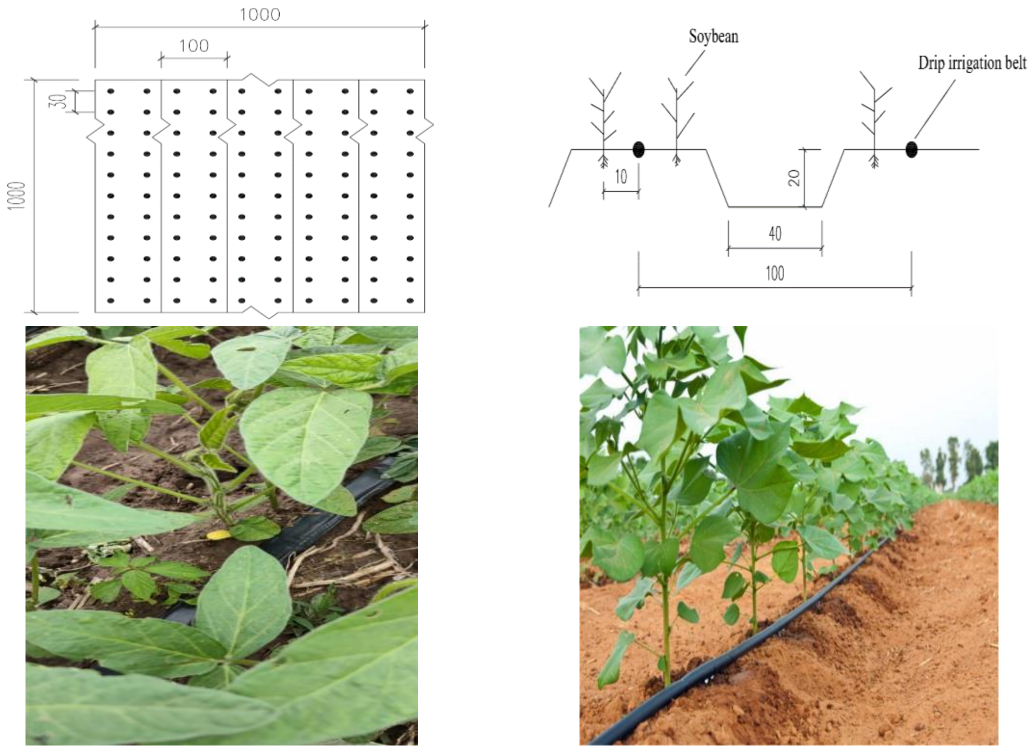

Figure 1. *A diagram of the test site in the field. (The dimensions in the figure are cm)*

Table 1. *Experiment treatment in the plot*

Treatment	Drip amount (mm)	Nitrogen applied (kg/hm^2)
W1N4	300	90
W2N4	350	90
W3N4	400	90
W1N3	300	81
W2N3	350	81
W3N3	400	81
W1N2	300	72
W2N2	350	72
W3N2	400	72
W1N1	300	63
W2N1	350	63
W3N1	400	63
W1N0	300	0
W2N0	350	0
W3N0	400	0
CK	0	90

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Determination and analysis method

Water use efficiency

(1) Soil moisture content

Soil moisture content was measured by TDR at a measuring point every 10 cm at a depth of 1 m. Soil moisture content was measured every 7–10 days before and after irrigation and after rainfall. In this study, a time-domain reflectometer was used for TDR, manufactured by Campbell Company in the United States.

(2) Water consumption of crops

The water balance equation was used to calculate the water consumption of crops in each growth stage and the whole growth period:

$$ET = P + I + S + \text{delta } W - R - D \quad \text{(Eq.1)}$$

In the equation, ET is crop water consumption (mm), P is precipitation (mm), I is irrigation amount (mm), S is groundwater recharge (mm), $\triangle W$ is the change of soil moisture content (mm), R is surface runoff (mm), D is deep leakage (mm). Groundwater recharge and deep leakage were ignored, but the influence of surface runoff (R) and deep leakage (D) were considered in heavy rain or extremely heavy rain.

(3) Water use efficiency

The following formula was used to calculate WUE.

$$WUE = Y / ET_m. \ WUEd = Yd / ET_m \quad \text{(Eq.2)}$$

In the equation, WUE is the water use efficiency calculated by soybean economic yield (kg/m^3). Y is soybean economic yield (kg/hm^2). ET_m is water consumption during crop growth period (mm). WUEd is the water use efficiency calculated by total dry matter mass of overground part (kg/m^3). Yd is dry matter mass of in the above-ground part of the soybean.

Nitrogen use efficiency

The following formula was used to calculate nitrogen use efficiency:

$$NUE = (y - y0) / (u - u0) \quad \text{(Eq.3)}$$

where Y is the crop yield (kg/hm^2) under fertilization. Y0 is crop yield (kg/hm^2) without fertilization. U is the total amount of fertilizer uptake (kg/hm^2) from the overground during harvest after fertilization. U0 is the total amount of fertilizer uptake from the aboveground of unfertilized crops (kg/hm^2) at harvest time.

The formula for calculating the apparent residual rate of nitrogen fertilizer was as follows: residual in area where nitrogen was not applied / fertilizer amount ×100%.

Yield

During the harvest period, each plot selected 2 m^2 of uniform and representative growth for yield measurement. After harvest, 10 plants were randomly selected to

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determine yield components, check the number of plants in square meters, the number of seeds per plant, and the weight of 100 seeds. Finally, the harvested soybeans were threshed after drying and actually measured yield.

Data processing

Microsoft Excel 2010 and Surfer software were used for data processing, and SPSS was used for variance analysis. Microsoft Excel 2010 and Surfer software are used in sections 2.1 to 2.3, and SPSS software is used in section 2.4.

Result analysis

Influence of different water and nitrogen treatments on water consumption during growth period

The water consumption of soybean at different growth stages is shown in *Table 2*. The water consumption of soybean increases with the growth of drip irrigation mode amount. The water consumption of each treatment is the largest at the bulking stage, followed by the flowering and pod stage. Except seedling stage, W3N4 treatment had the highest water consumption, with a total water consumption of 644.59 mm. W1N4 treatment had the lowest water consumption, with a total water consumption of 392.62 mm, which was 66.97% and 1.70% higher than the control group (CK), respectively. There was no significant difference in water consumption among different treatments at seedling stage, irrigation treatment had significant difference in water consumption of soybean at branching stage, flowering and pod stage and seed filling stage. While nitrogen factor had no significant difference in water consumption of soybean, and their interaction had significant difference in water consumption of soybean.

Table 2. *water consumption of soybean in different growth periods*

Treatment	Water consumption/mm				
	Seeding period	Branching period	Flowering and pod stage	Seed filling stage	Total amount of water consumption
W1N4	40.74	55.27	131.71	164.9	392.62
W2N4	41.78	85.23	187.79	197.44	512.23
W3N4	44.01	138.36	216.57	245.65	644.59
W1N3	40.83	86.31	171.19	193.22	491.56
W2N3	41.51	95.05	176.07	173.15	485.78
W3N3	45.59	119.61	269.52	190.99	625.71
W1N2	41.19	106.28	117.26	170.42	435.15
W2N2	41.87	111.38	159.93	171.95	485.13
W3N2	46.18	118.32	206.72	239.53	610.74
W1N1	38.79	100.93	112.98	173.23	425.93
W2N1	41.38	106.86	147.8	183.45	479.49
W3N1	45.34	123.26	216.57	207.22	592.4
W1N0	37.08	56.18	116.62	140.08	349.96
W2N0	40.17	82.17	184.55	154.54	461.43
W3N0	41.6	94.23	185.56	167.83	489.22
CK	42.42	51.15	137.49	154.98	386.04
W	2.01	12889.66**	20.64**	1.89*	39.27*
N	0.34	38.93	0.69	0.69	0.24
W×N	0.98	297.62	1.76*	0.63	0.75
Average	41.91	95.66	171.15	183.04	491.75

Data are mean values of 3 quadrats, lowercase letters represent significant difference at P = 0.05 level, * represents significant difference (P < 0.05), ** represents extremely significant difference (P < 0.01)

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Soybean yield without water and nitrogen coupling treatment

The output of each treatment under different water-nitrogen coupling is shown in *Figure 2*. It can be seen from *Figure 2* that, W1, W2 and W3 treatments had significant differences ($P < 0.05$) at the N3 level. W3N3 treatment had the highest yield of 3250 kg/hm^2, which increased by 16.10% and 29.22% compared with W1N3 treatment. With the growth of irrigation amount, the yield increased, but the yield increase rate became slow. The yield of increasing irrigation amount increased in different degrees. At the W3 level, there was significant difference between N0 and N4 fertilization treatments ($P < 0.05$), and the yield of the four treatments increased by 28.31%, 48.40%, 29.22% and 13.93%, respectively, compared with that of W3N0 treatment. With the growth of nitrogen application rate, the yield showed a trend of first increasing and then decreasing. When the irrigation amount was constant, an appropriate increase of nitrogen application rate was beneficial to increase the yield.

When the nitrogen application rate was low (N0–N3), there was a positive interaction between water and nitrogen, which showed a synergistic promoting effect. When the amount of nitrogen was constant, increasing the amount of irrigation in a certain range could effectively increase crop yield, and soybean was in the state of high nitrogen application efficiency. When the nitrogen application rate was higher than the level of N3 and the irrigation amount was at the level of W1–W3, the soybean was in the state of slow effect or ineffective nitrogen application. The crop yield reached the maximum, when the nitrogen application rate was 81 kg/hm^2 and the irrigation amount was 400 mm. When nitrogen application rate was greater than 81 kg/hm^2, there was a negative interaction between water and nitrogen, and excessive nitrogen application rate had toxic effects on crops.

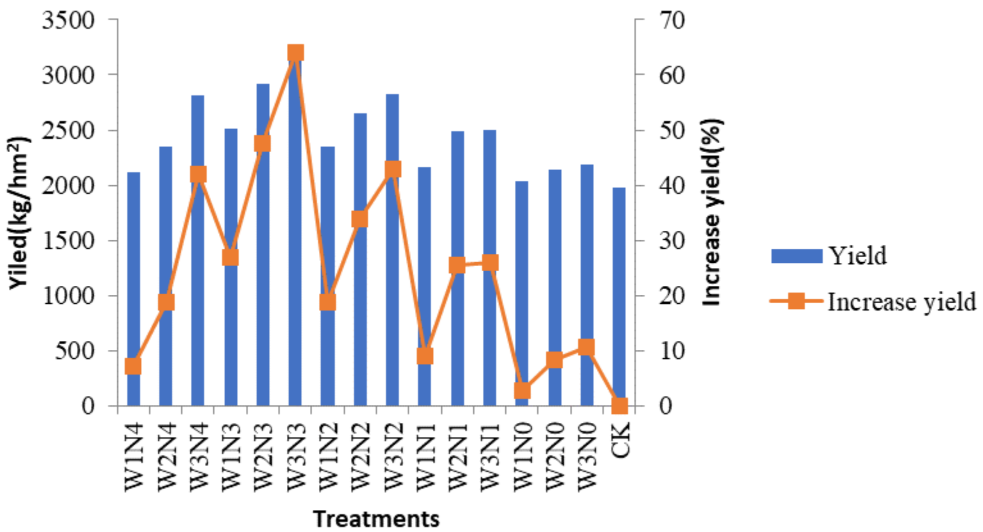

Figure 2. *The yield of soybean under the influence of water nitrogen coupling effect*

Effects of different water and nitrogen treatments on water use efficiency and nitrogen use efficiency of soybean

Water and nitrogen use efficiency of each treatment were shown in *Figure 3*. The WUE of W2N3 treatment was at 0.60 kg/m^3, 17.65% higher than CK treatment. At the

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same level of nitrogen application, WUE increased with the growth of irrigation amount at N1 and N2 levels, and increased first and then decreased with the growth of irrigation amount at N3 level. It can be seen that increasing irrigation amount within a certain range of nitrogen application can help increase WUE, but when is over a certain range, WUE decreased. Under N3 and N4 levels, the nitrogen application rate is higher, the WUE was lower. Under W1 and W2 irrigation treatments, there was no significant difference in the nitrogen application rate at N0, N1 and N2 levels compared with the blank control, and WUE of soybean was not increased, while under excessive nitrogen application (N3 and N4) conditions, WUE of W1N4 and WN3 was lower than that of W1N2 and W1N1 treatments. WUE increased first and then decreased with the growth of nitrogen application rate under W3 irrigation treatment. W2N3 treatment improved WUE although the irrigation amount was less than W3N3 treatment. Therefore, it could be seen that high water and high fertilizer did not improve WUE.

It can be seen from *Figure 3* that the nitrogen use efficiency of soybean was 29.11%–44.62%. At the N3 level, there were significant differences among W1, W2 and W3 treatments. At W3 level, the difference between N3 and N4 treatment was significant, showing that N3 treatment was higher than N4 treatment. In general, the use efficiency decreased with the growth of application rate. Appropriate irrigation increased n uptake and n use efficiency, while excessive irrigation did not increase N use efficiency significantly (W2N4 and W3N4 treatments, W2N3 and W3N3 treatments had no significant difference). The utilization efficiency of NITROGEN fertilizer in W3N3 treatment was 53.28% higher than that in W0N3 treatment.

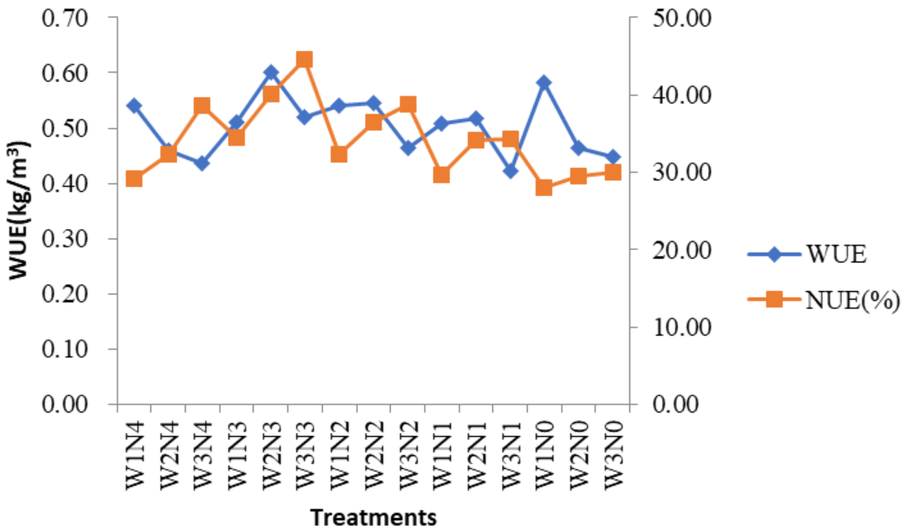

Figure 3. *The effect of different water and nitrogen treatment to the "water user efficiency" of soybean*

Effects of different water and nitrogen treatments on soybean nitrogen residual

The residual inorganic nitrogen in the 0–100 cm soil layer of soybean after harvest is mainly nitrate nitrogen. Therefore, only the residual nitrate nitrogen is considered when evaluating the post-harvest mineral nitrogen of crops. It can be seen from *Figure 4* that, after crop harvest, the soil nitrate nitrogen in 0-100 cm soil layer showed significant differences among N1, N2 and N3 treatments (The nitrogen application amount is

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higher, the residual nitrogen was greater, N1 treatment was 61.7–63.7 kg/hm^2, N2 treatment was 69.7–72.6 kg/hm^2, N3 treatment is 99.2–117.4 kg/hm^2, N3 treatment is 138.6–159.4 kg/hm^2). Compared with W3N4 treatment, the nitrate nitrogen residue in W3N3 treatment with the highest yield was reduced by 42 kg/hm^2 (35.78%), indicating that proper combination of water and nitrogen application can reduce nitrogen residue in soil after crop harvest.

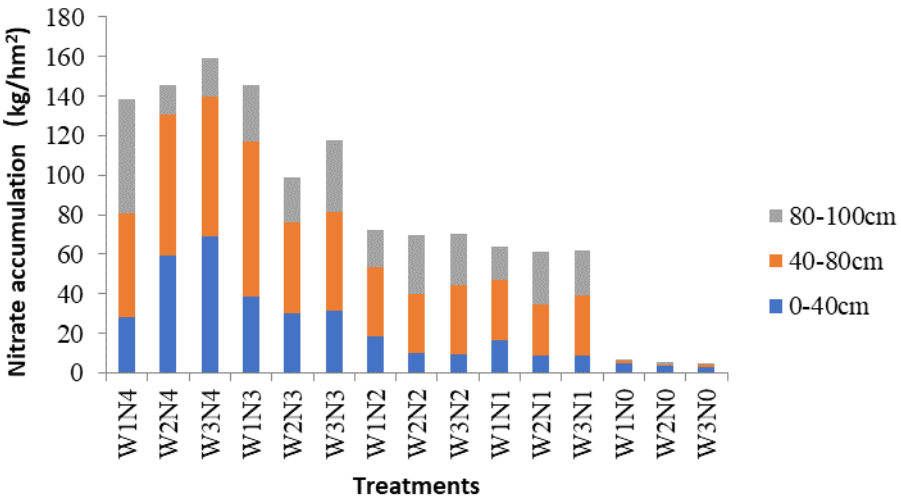

Figure 4. *Accumulation of residual nitrate nitrogen in different soil layers under different water and nitrogen treatments*

Discussion

Water and fertilizer are two important limiting factors in agricultural production, and their interaction has a significant impact on yield (Qiao et al., 2007; Jia et al., 2017). Irrigation treatment had a significant effect on soybean water consumption, but fertilization had no significant effect on soybean water consumption, and the interaction between irrigation and fertilization had a significant effect on soybean water consumption at flowering and pod stage. The largest water consumption of soybean treatment was W_3N_4, which was 400 mm drip irrigation mode, with 90 kg/hm^2 nitrogen application, and 644.59 mm total water consumption. The maximum yield treatment was W_3N_3, that is, the drip irrigation mode amount was 400 mm, nitrogen application amount was 81 kg/hm^2, and the yield was 3250 kg/hm^2. The results of this study are slightly different from those of Sun et al. (2018), which may be caused by the fact that the research area is Inner Mongolia, the climate and geological conditions are different from those of this study. WUE of W_2N_3 treatment was the highest, i.e., Drip irrigation mode amount was 350 mm, nitrogen application amount was 81 kg/hm^2, and WUE was 0.60 kg/m^3. High water and high fertilizer did not improve yield, and WUE of high water and low fertilizer was low, which was basically consistent with the research results of Han et al. (2006) and Feng and Zhang (2011).

The application of chemical fertilizer plays a significant role in the improvement of yield, but the improvement of fertilizer use efficiency should be ensured at the same time (Peng et al., 2002), and 30%-50% nitrogen use efficiency of crops is more appropriate (Wu et al., 2008). In this experiment, nitrogen use efficiency was 29.11%–

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44.62% under different water and nitrogen treatments, which was smaller than the conclusion drawn by Dai and Cheng (2000) and Ji et al. (2009). The large fertilizer loss caused by no irrigation and excessive fertilizer application under high nitrogen application level.

In agricultural production, long-term application of a large amount of chemical fertilizer in order to improve yield results in the accumulation of nitrate nitrogen, which increases with the growth of nitrogen application rate. Unreasonable irrigation and fertilization will not only be difficult to increase yield, but also increase nitrate nitrogen accumulation in soil profile, reduce crop quality and water and nitrogen use efficiency. Nitrate downward migration velocity increases with the growth of irrigation quota and high-water fertilizer leaching risk (Sui et al., 2014), a large amount of residual N_2O_3 easy through leaching nitrification, denitrification is lost from the soil and root system, cause harm to the environment (Wang et al., 2010), reasonable adjust water applying nitrogen content, can increase the absorption of crop on soil N_2O_3, and reduce nitrate accumulation (Xing et al., 2015; Lu et al., 1998). In this experiment, W_3N_3 treatment ensured crop yield and reduced soil nitrate nitrogen residue level, which was 42 kg/hm^2 lower than W_3N_4 treatment (0-100 cm soil layer). This is consistent with the research conclusions of Liu et al. (2020) and Li et al. (2021). Although the water and nitrogen use efficiency of black soil soybean was analyzed in this study, there was no in-depth study on its mechanism. In the next step, based on the experimental data, the models of water, fertilizer and soybean water use efficiency and yield will be established, and the simulation results will be verified with the analysis results.

Conclusion

(1) The water consumption of soybean increased with the growth of drip irrigation mode amount, and the water consumption was the largest in the bulking stage, followed by the flower pod stage. There was no significant difference in water consumption among different treatments at seedling stage, but there was significant difference in water consumption at branching stage, flowering and pod stage, and bulking stage. There was no significant difference in water consumption between nitrogen fertilizer and soybean, but the interaction between nitrogen fertilizer and soybean had significant difference in water consumption.

(2) At the level of 81 kg/hm^2 of nitrogen application, there were significant differences among drip irrigation mode treatments ($P < 0.05$). When the drip irrigation mode amount was 400 mm and the nitrogen application amount was 81 kg/hm^2, the maximum yield was 3250 kg/hm^2. With the growth of irrigation amount, the yield increased, but the yield increase rate became slow. Therefore, when the nitrogen application rate was at a low level (0–81 kg/hm^2), there was a positive interaction between water and nitrogen, which showed a synergistic promoting effect. When the nitrogen application rate was greater than 81 kg/hm^2, there was a negative interaction between water and nitrogen, and excessive nitrogen application rate had toxic effects on crops.

(3) This study is based on experimental analysis. Under drip irrigation mode, different water and fertilizer application rates are used to improve water and nitrogen utilization rate and yield, which is of great significance for scientifically formulating water-saving and yield increasing (stable) management strategies for black soil soybean.

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