ChinaRxiv 中X

AI translation · View original & related papers at
chinarxiv.org/items/chinaxiv-201801.00065

Effects of Nitrogen Application Rate on Nitrogen Uptake and Utilization by Summer Maize and Soil Nitrate-N Content under Drip Fertigation (Postprint)

Authors: Guo Li, Jianshuo Shi, Wang Liying, Li Ruonan, Ren Yanli, Zhang Yancai

Date: 2018-01-05T00:00:00+00:00

Abstract

Unreasonable fertilization practices are widespread in the high-yield summer maize region of the Hebei Piedmont Plain, resulting in serious agricultural non-point source pollution. Investigating the optimal nitrogen fertilizer management for summer maize under integrated water-fertilizer conditions in the North China Piedmont Plain can provide a basis for optimized nitrogen application technology and improved nitrogen use efficiency in this region. This study, using the 'Zhengdan 958' maize variety as experimental material, established four nitrogen application levels under drip irrigation conditions during two maize growing seasons in 2014-2015 (N0: no nitrogen; N1: 120 kg · hm-2; N2: 240 kg · hm-2; N3: 360 kg · hm-2) to investigate the effects of nitrogen application rate on nitrogen absorption and utilization in maize and soil nitrate nitrogen content under integrated drip irrigation water and fertilizer management. The results showed that the dry matter weight and yield of maize under N0 treatment were significantly lower than those of other treatments, while no significant differences were observed among N1-N3 treatments. The nitrogen content and nitrogen accumulation of maize under N1 treatment were significantly increased compared with N0 treatment. Within the N1-N3 nitrogen application range, there were certain differences in maize plant nitrogen content and nitrogen accumulation between different years, showing an overall trend of increasing with nitrogen application rate; however, the increase magnitude of plant nitrogen content and nitrogen accumulation gradually decreased with increasing nitrogen application rate. N2 treatment had the highest nitrogen harvest index. With increasing nitrogen application rate, nitrogen recovery efficiency, nitrogen agronomic efficiency, nitrogen production efficiency, and nitrogen use efficiency decreased significantly. In 2014, nitrate nitrogen content gradually decreased within the

0-100 cm soil profile under the same nitrogen application rate. In 2015, soil nitrate nitrogen at nitrogen application rates of 240 kg · hm-2 and 360 kg · hm-2 reached an accumulation peak at the 100 cm soil depth. After two years of cultivation, when nitrogen application rate exceeded 240 kg · hm-2, soil nitrate nitrogen leaching intensified, being leached to the 100 cm soil layer. Using a quadratic equation to fit the relationship between yield and nitrogen application rate, the nitrogen application rate for maximum maize yield was determined to be 199-209 kg · hm-2, and the economic nitrogen application rate was 174-187 kg · hm-2. Considering both economic and ecological benefits comprehensively, the economic nitrogen application rate is recommended for drip irrigation nitrogen application in summer maize under these conditions.

Full Text

Effects of Nitrogen Application Rate on Nitrogen Absorption, Utilization, and Soil Nitrate-N Content in Summer Maize under Drip Fertigation

GUO Li, SHI Jianshuo, WANG Liying, LI Ruonan, REN Yanli, ZHANG Yancai
(1. Institute of Agricultural Resources and Environment, Hebei Academy of Agriculture and Forestry Sciences, Shijiazhuang 050051, China;
2. Hebei Fertilizer Engineering Technology Research Center, Shijiazhuang 050051, China)

Abstract: Improper fertilization management is widespread in the high-yield summer maize production region of the Hebei piedmont plain, resulting in serious agricultural non-point source pollution. This study investigated optimal nitrogen management for summer maize under water-fertilizer integration conditions in the North China piedmont plain, providing a basis for optimizing nitrogen application technology and improving nitrogen use efficiency. Using the 'Zhengdan 958' maize variety as test material, four nitrogen application rates (N0: 0 kg · hm ^{2}; N1: 120 kg · hm ^{2}; N2: 240 kg · hm ^{2}; N3: 360 kg · hm ^{2}) were established under drip irrigation during two summer maize growing seasons (2014–2015) to examine the effects of nitrogen rate on nitrogen uptake, utilization, and soil nitrate-N content. The results showed that dry matter weight and grain yield under N0 were significantly lower than under other treatments, with no significant differences observed among N1–N3 treatments. Nitrogen content and accumulation under N1 were significantly higher than under N0. Within the N1–N3 range, plant nitrogen content and accumulation showed some variation between years, but generally increased with nitrogen application rate, though the rate of increase gradually declined. The nitrogen harvest index was highest under N2 treatment. Nitrogen recovery efficiency, agronomic efficiency, productive efficiency, and use efficiency all decreased significantly with increasing nitrogen application rate. In 2014, soil nitrate-N content decreased gradually with soil depth (0–100 cm) at the same nitrogen rate. In 2015, nitrate-N accumulated at the 100 cm depth under N2 and N3 rates. After two years of cultivation, nitrate-N leaching was intensified when nitrogen application exceeded 240 kg · hm ^{2}, with nitrate being leached to the 100 cm soil layer. Using a quadratic equation to fit the relationship between yield and nitrogen rate, the nitrogen application rates for maximum yield were determined to be 199-209 kg · hm ^{2}, while the economically optimal rates were 174–187 kg · hm ^{2}. Considering both economic benefits and ecological impacts, the economically optimal nitrogen application rate is recommended for summer maize under drip fertigation conditions.

Keywords: Drip fertigation; Summer maize; Nitrogen application rate; Nitrogen uptake and utilization; Soil nitrate-N content
Chinese Classification Code: S143.3
Document Code: A

Maize is a crucial grain crop in North China and across the nation, and ensuring stable high yields is vital for national economic development. However, this region suffers from drought and low rainfall, with severe water shortages. Agricultural water consumption accounts for 78.82% of total groundwater extraction[1], making rational water resource development and utilization a critical strategic priority for North China. Drip fertigation delivers fertilizers directly to plant root zones through irrigation systems, enabling precise control of water and fertilizer application. This technology allows accurate regulation of water and nutrient quantities and ratios based on soil conditions and crop growth stages, maximizing water-fertilizer coupling effects, improving use efficiency, and reducing nutrient losses. By providing optimal water and nutrient conditions, drip fertigation improves soil microenvironments and substantially increases crop yields. Research indicates that compared with conventional irrigation, drip irrigation saves 40% water and 30% compared with sprinkler irrigation[2-3], while nitrogen use efficiency under fertigation reaches 75%-80% versus only 40% with conventional fertilization[4]. Drip fertigation has been widely adopted in agriculturally developed countries such as Israel, the United States, and Australia[5-7]. In China, however, drip fertigation for field crops has only been partially implemented in the arid northwest regions. In Xinjiang, drip-fertigated maize has achieved super-high yields with nitrogen partial productivity and use efficiency increasing to 122 kg(N) · hm ^{2} and 45%, respectively[8]. The application of integrated drip fertigation technology remains limited in North China’ s maize production. Investigating optimal nitrogen rates under drip fertigation can reduce environmental pollution, conserve valuable water resources, and effectively alleviate excessive exploitation of deep groundwater in this region.

Nitrogen is the most critical nutrient element affecting maize yield and quality, playing an essential role in crop growth and development. Appropriate and timely nitrogen supply not only improves yield and quality but also minimizes nitrogen leaching losses, which is significant for environmental protection. To date, numerous scholars have investigated nitrogen accumulation, distribution, utilization efficiency, and leaching in maize in relation to genotype[9], nitrogen type[10], application rate[11], timing and frequency[12-14], and cultivation methods. For example, in Jilin Province, Northeast China, reasonable nitrogen rates should be controlled at 180–240 kg·hm ^{2} based on grain yield, nitrogen use efficiency, and soil nitrate accumulation[15]. In the central Heilonggang River Basin of the North China Plain, a nitrogen rate of 180 kg · hm ^{2} satisfies nitrogen requirements for various organs and achieves high yield and efficiency[16]. In Xinjiang' s Ulan region, drip fertigation studies have shown maize yields of 17,109–17,138 kg·hm ^{2} with economically optimal nitrogen rates of 427.9–467.7 kg · hm ^{2}[8]. However, previous research on nitrogen effects on maize nitrogen utilization and environmental impacts in North China has primarily focused on surface flood irrigation with single basal and topdressing applications. Although drip fertigation is partially adopted in Northwest China, significant differences exist in light, temperature, vapor, and heat conditions compared with North China. Therefore, the responses of nitrogen uptake, utilization, and soil nitrate content to nitrogen application rates under drip fertigation in the piedmont plain of North China require urgent clarification. This two-year field study investigated the effects of different nitrogen rates on maize dry matter accumulation, grain yield, nitrogen uptake and use efficiency, and soil nitrate-N content under drip irrigation conditions, aiming to establish optimized fertilization techniques for integrated drip fertigation of maize in the Hebei piedmont plain and provide technical support for synergistic high yield, water resource conservation, and efficient nitrogen utilization in this region.

1.1 Experimental Site Description

This experiment was conducted in 2014 and 2015 at the Lüquan Agricultural Environment Field Observation Station of the Ministry of Agriculture (38°12 N, 114°38 E). The cropping system followed a winter wheat–summer maize rotation. Rainfall during the maize seasons was 246 mm in 2014 and 329 mm in 2015. The region belongs to the piedmont plain of the North China Plain, with calcareous cinnamon soil of clay-loam texture derived from flood alluvium. The baseline soil properties in the 0–20 cm layer were: nitrate-N 11.28 mg · kg ^{1}, available phosphorus 14.6 mg · kg ^{1}, and available potassium 85.0 mg · kg ^{1}. The maize variety tested in both 2014 and 2015 was 'Zhengdan 958' .

1.2 Experimental Design

The experiment consisted of four nitrogen treatments: 0, 120, 240, and 360 kg · hm ^{2}, designated as N0, N1, N2, and N3, respectively. A randomized complete block design was employed with three replications, and each plot area was 64 m^{2}. Phosphorus and potassium fertilizer rates were consistent across all treatments at 105 kg P O · hm ^{2} and 270 kg K O · hm ^{2}. For basal application, 40% of nitrogen and potassium fertilizers and 80% of phosphorus fertilizer were applied. The remaining nitrogen, phosphorus, and potassium were formulated as water-soluble solid fertilizers and applied through drip fertigation at three growth stages: jointing, silking, and grain filling, with each topdressing accounting for one-third of the total topdressed amount. Basal nitrogen fertilizer was urea, phosphorus fertilizer was diammonium phosphate (single superphosphate for N0 treatment), and potassium fertilizer was potassium chloride. Topdressing fertilizers for drip fertigation consisted of urea for nitrogen, monoammonium phosphate for phosphorus, and potassium chloride for potassium. Summer maize was irrigated four times during the entire growth period. Irrigation amounts were determined based on crop growth stage and soil moisture conditions: 450 m^3 · hm ^{2} at sowing, and 150–180 m^3 · hm ^{2} for each fertigation event.

1.3.1 Plant Dry Matter Weight

Five representative plants with uniform growth were sampled from each plot at the jointing, silking, grain filling, and maturity stages of summer maize. Samples were killed at 105 °C for 30 minutes and then dried at 75 °C to constant weight to calculate dry matter weight per unit area.

1.3.2 Plant Nitrogen Content

The five plants used for dry weight determination at each growth stage were separated into different organs, killed at 105 °C for 30 minutes, dried at 75 °C to constant weight, and ground. Total nitrogen content in various plant organs was determined by the Kjeldahl method after digestion with concentrated sulfuric acid. Plant nitrogen content was calculated using the weighted average method. Formulas for nitrogen uptake and utilization calculations[7,8,10,13] were as follows:

Nitrogen accumulation = Nitrogen content (%) × Dry matter weight (1)
Nitrogen harvest index (%) = Grain nitrogen uptake / Aboveground nitrogen accumulation (2)
Nitrogen recovery efficiency (%) = (Total aboveground nitrogen uptake in N-fertilized plots at harvest –Total aboveground nitrogen uptake in N0 plots at harvest) / Nitrogen application rate × 100 (3)
Nitrogen agronomic efficiency (kg · kg ^{1}) = (Grain yield in N-fertilized plots – Grain yield in N0 plots) / Nitrogen application rate (4)
Nitrogen productive efficiency (kg · kg ^{1}) = Grain yield / Nitrogen application rate (5)
Nitrogen use efficiency (kg · kg ^{1}) = Grain yield / Aboveground nitrogen accumulation (6)
Economically optimal nitrogen rate (kg · hm ^{2}) = –(b –Px/Py) / 2a (7)

Where: *a* is the linear coefficient and *b* is the quadratic coefficient from the quadratic equation fitting yield and nitrogen rate; Px is nitrogen fertilizer price (4.96 yuan · kg ^{1}); Py is maize price (2.0 yuan · kg ^{1})[17].

1.3.3 Soil Nitrate-N Content Determination

At summer maize maturity, soil samples were collected from the 0–100 cm profile using a soil auger at 20 cm intervals. Samples were immediately placed in sealed bags and stored at -20 °C. For analysis, soil samples were thawed, mixed thoroughly, and passed through a 2 mm sieve. A 12 g subsample was extracted with 50 mL of 1 $\text{mol}\cdot\text{L}^{1}$ KCl solution for 1 hour, and nitrate-N concentration in the extract was determined by UV spectrophotometry. Soil water content was measured simultaneously to calculate nitrate-N content on a dry soil basis.

1.3.4 Grain Yield

At maturity, two 2 m^2 areas were harvested in each plot. Grain was threshed using a small thresher, air-dried, and grain moisture content was measured. Yield was then converted to a standard moisture content of 13%.

1.4 Data Processing

Data processing and statistical analysis were performed using Microsoft Excel 2007 and SPSS 19.0 software for statistical analysis and significance testing.

2.1 Effects of Nitrogen Rate on Maize Dry Matter Accumulation under Drip Fertigation

The response of maize dry matter accumulation to nitrogen application rate is shown in Figure 1 [Figure 1: see original paper]. In 2014, dry matter accumulation under N0 at the jointing stage was significantly lower than under N1 and N2, but not significantly different from N3. At the grain filling stage, N0 dry matter accumulation was significantly lower than N1, N2, and N3, with no significant differences among the latter three treatments. At maturity, dry matter accumulation showed similar trends to those at jointing. In 2015, the effects of nitrogen treatments on dry matter accumulation showed that at jointing, N2 and N3 were significantly higher than N0. At grain filling and harvest, N1, N2, and N3 were significantly higher than N0, but showed no significant differences among themselves. These results indicate that under drip fertigation conditions, maize dry weight increased linearly with nitrogen rate in the 0–120 $\text{kg}\cdot\text{hm}^{2}$ range, but showed no significant response to nitrogen rates between 120 and 360 $\text{kg}\cdot\text{hm}^{2}$.

2.2 Effects of Drip Fertigation Nitrogen Rate on Plant Nitrogen Content and Accumulation

The response of maize plant nitrogen content and accumulation at different growth stages to nitrogen application rate under drip fertigation is presented in Table 1 . In 2014, plant nitrogen content at all growth stages under N0 was significantly lower than under N1, N2, and N3. Among N1–N3 treatments, no significant differences in plant nitrogen content were observed at jointing, while at silking, grain filling, and maturity, N3 was significantly higher than N1 but not significantly different from N2. In 2015, nitrogen-fertilized treatments showed significantly higher plant nitrogen content than N0 at all growth stages. Comparisons among N1, N2, and N3 revealed no significant differences at jointing, grain filling, and maturity, but at silking, nitrogen content followed the order N1 < N2 < N3 with significant differences. Despite some inter-annual variation, plant nitrogen content generally increased with nitrogen application rate.

In 2014, nitrogen accumulation at all growth stages under N0 was significantly lower than under fertilized treatments. Among fertilized treatments (Table 1), no significant differences were observed among N1, N2, and N3 at jointing, while at silking, grain filling, and maturity, N3 was significantly higher than N1, though N2 and N3 showed no significant differences. In 2015, nitrogen accumulation under N0 was significantly lower than under fertilized treatments at all stages. Comparisons among N1, N2, and N3 showed no significant differences at jointing and grain filling. At silking, N1 was significantly lower than N3, while at maturity, N3 showed the highest nitrogen accumulation, significantly different from N1 and N2. In summary, nitrogen accumulation in maize at different growth stages in both 2014 and 2015 generally increased with nitrogen application rate, but the incremental effect diminished when nitrogen rates exceeded 120 kg · hm ^{2}.

2.3 Effects of Drip Fertigation Nitrogen Rate on Grain Yield and Nitrogen Use Efficiency

In 2014, maize grain yield under N0 was significantly lower than under N1 and N2 (Table 2). Nitrogen harvest index under N0 and N1 was significantly higher than under N2 and N3, with no significant difference between N2 and N3. Nitrogen recovery efficiency and agronomic efficiency under N2 and N3 were significantly lower than under N1, though N2 and N3 did not differ significantly. Nitrogen productive efficiency was highest under N1, significantly higher than N2 and N3. Nitrogen use efficiency showed a decreasing trend with increasing nitrogen rate, with N3 significantly lower than N0 and N1 but not significantly different from N2. In 2015, grain yield was highest under N1, significantly higher than N0 but not significantly different from N2 and N3. Nitrogen harvest index under N0 and N1 was significantly higher than under N2 and N3. Nitrogen recovery efficiency, agronomic efficiency, and productive efficiency showed similar trends to 2014, while nitrogen use efficiency decreased with increasing nitrogen rate. These results indicate that over two consecutive years, grain yield and nitrogen harvest index within the 120–360 kg · hm ^{2} nitrogen range showed a parabolic trend, initially increasing then decreasing with nitrogen rate. Nitrogen recovery efficiency, agronomic efficiency, productive efficiency, and use efficiency all decreased gradually with increasing nitrogen application.

2.4 Effects of Drip Fertigation Nitrogen Rate on Soil Nitrate-N Content

The response of soil nitrate-N content in the 0–100 cm profile to nitrogen application rate at harvest is shown in Figure 3 [Figure 3: see original paper]. In the 2014 maize harvest season, nitrate-N content in the 0–20 cm layer under N2 and N3 was significantly higher than under N0 and N1, with no significant difference between N2 and N3. In soil layers below 40 cm, nitrate-N content across treatments showed an increasing trend with nitrogen application rate. At the same nitrogen rate, nitrate-N content decreased gradually with soil depth. In 2015, the trend of nitrate-N content among treatments at the same soil depth was similar to 2014, with higher nitrogen rates resulting in higher soil nitrate-N content. Variations in nitrate-N content across soil layers at the same nitrogen rate showed that under N0, nitrate-N decreased gradually with depth. Under N1 and N2, nitrate-N decreased in the 0–60 cm layer but increased in the 60–100 cm layer. Under N3, nitrate-N content increased with soil depth, with significant increases in the 60–100 cm layer.

In summary, in 2014, nitrate-N content decreased gradually with depth (0–100 cm) at the same nitrogen rate. In 2015, nitrate-N accumulated at the 100 cm depth under nitrogen rates of 240 and 360 kg · hm ^{2}. This indicates that after two years of cultivation, nitrate-N was leached to the 100 cm soil layer at nitrogen rates of 240 and 360 kg · hm ^{2}.

2.5 Economically Optimal Nitrogen Rate for Drip-Fertigated Summer Maize

Rational nitrogen application is critical for increasing maize yield. A quadratic equation was used to analyze the relationship between grain yield and nitrogen rate, and to calculate the nitrogen rates for maximum yield and economic optimum (Figure 3 [Figure 3: see original paper]). In 2014, the fitted equation had a coefficient of determination (R^2) of 0.886 and a correlation coefficient of 0.94; in 2015, R^2 was 0.748 and the correlation coefficient was 0.86. These results demonstrate that the quadratic equation adequately described the relationship between maize yield and nitrogen rate under drip fertigation. The fitted equations indicated that nitrogen rates for maximum yield were 208.7 and 199.8 kg · hm ^{2} in 2014 and 2015, respectively, while economically optimal nitrogen rates were 186.4 and 174.2 kg · hm ^{2}, respectively. In summary, under the soil fertility conditions of this experiment, the nitrogen rate for maximum yield of drip-fertigated maize in the piedmont plain was 199–209 kg · hm ^{2}. Considering both economic benefits and ecological impacts, the economically optimal nitrogen rate was 174–187 kg · hm ^{2}.

2.6 Correlation Analysis of Various Indices

Correlation analysis among maize yield, nitrogen application rate, and nitrogen use efficiency parameters under drip fertigation is presented in Table 3 .

Nitrogen application rate showed highly significant negative correlations with nitrogen recovery efficiency, agronomic efficiency, and productive efficiency, a significant negative correlation with nitrogen use efficiency, and a highly significant positive correlation with nitrogen uptake. Grain yield showed no significant correlations with nitrogen rate or nitrogen use efficiency parameters. Nitrogen harvest index was highly significantly positively correlated with nitrogen productive efficiency and use efficiency, and significantly correlated with nitrogen agronomic efficiency. Nitrogen recovery efficiency was highly significantly positively correlated with nitrogen agronomic efficiency and significantly positively correlated with nitrogen productive efficiency. Nitrogen agronomic efficiency was highly significantly positively correlated with nitrogen productive efficiency and negatively correlated with nitrogen uptake. Nitrogen productive efficiency was significantly positively correlated with nitrogen use efficiency and highly significantly negatively correlated with nitrogen uptake. Nitrogen use efficiency was significantly negatively correlated with nitrogen uptake. These results indicate that while nitrogen application rate has a significant positive correlation with plant nitrogen uptake, it negatively correlates with nitrogen recovery efficiency, agronomic efficiency, productive efficiency, and use efficiency, and shows no significant correlation with grain yield.

Discussion

Compared with conventional irrigation, drip fertigation represents a shift from field-scale to plant-scale watering, from soil fertilization to plant fertilization, from separate water and fertilizer application to synchronized application, from single management approaches to integrated management, and from traditional to modern agriculture. Therefore, developing integrated water-fertilizer technology is a major modern agricultural technique for achieving high yield and quality, efficient water and fertilizer use, and ecological safety[4]. With scarce water resources in North China, traditional flood irrigation can no longer meet production demands. It is necessary to adopt drip fertigation for summer maize to maximize the value of limited water resources in this region.

Numerous domestic and international production practices have confirmed that increasing nitrogen, phosphorus, and potassium application enhances photosynthetic products in summer maize, with nitrogen being particularly crucial for improving crop photosynthesis[18-19]. Many studies have reported on the effects of nitrogen rate on maize dry matter accumulation and nitrogen accumulation[15,20]. Research in Jiangsu showed that dry matter accumulation followed a unimodal curve within the 0–540 kg · hm ^{2} nitrogen range, peaking at 450 kg · hm ^{2}[21]. Spring maize in Jilin, Northeast China, showed no significant differences in dry matter and nitrogen accumulation when nitrogen rates exceeded 240 kg · hm ^{2}, though nitrogen application significantly promoted aboveground nitrogen absorption compared with N0[15]. These results were all obtained under flood irrigation and conventional fertilization conditions. Our study found that in the Hebei piedmont plain under drip fertigation, maize dry weight increased linearly with nitrogen rate in the 0–120 kg · hm ^{2} range, with no significant differences in dry matter accumulation at rates above 120 kg · hm ^{2}. Plant nitrogen accumulation increased gradually across the 0–360 kg · hm ^{2} range, with particularly strong effects in the 0–120 kg · hm ^{2} range. At rates above 120 kg · hm ^{2} up to 360 kg · hm ^{2}, the regulatory effect of increasing nitrogen rate on plant nitrogen accumulation gradually decreased, showing similar trends across years. These results differ somewhat from previous studies, possibly due to differences in fertilization methods, irrigation systems, and regional conditions.

Zhang et al. reported that a nitrogen rate of 180 kg · hm ^{2} in the low plain region of North China could achieve both high yield and high efficiency[16]. In Quzhou, Hebei, Xu et al. used ^{1} N isotopic tracing to explore relationships among fertilizer nitrogen, soil nitrogen, and crop nitrogen, finding that an optimized nitrogen rate of N kg · hm ^{2} for summer maize achieved high yield with high nitrogen use efficiency[22]. Our study showed that grain yield and nitrogen harvest index followed a unimodal curve, while nitrogen recovery efficiency, agronomic efficiency, productive efficiency, and use efficiency decreased with increasing nitrogen rate. Correlation analysis of nitrogen use parameters revealed positive correlations between nitrogen rate and nitrogen uptake, but negative correlations between nitrogen rate and uptake with agronomic efficiency, productive efficiency, and use efficiency. This indicates that as nitrogen application rate and total plant nitrogen uptake increase, plant nitrogen demand gradually decreases. Excessive nitrogen exceeds plant capacity for nitrogen translocation and utilization, leading to luxury consumption and reduced nitrogen use efficiency.

A quadratic equation was used to analyze the relationship between nitrogen rate and grain yield over two years. Based on the principle of marginal revenue equaling marginal cost, economically optimal nitrogen rates were determined to be 174 kg · hm ^{2} in 2014 and 187 kg · hm ^{2} in 2015. Based on yield and nitrogen harvest index results, combined with the economically optimal rates derived from equation fitting, the appropriate nitrogen rate for this region is 174–187 kg · hm ^{2} when considering both economic benefits and ecological impacts. Although these results are generally consistent with those of Zhang et al. and Xu et al.[16,22], our experimental site had lower baseline soil fertility while achieving higher grain yields than previous studies, indicating relatively improved nitrogen use efficiency under drip fertigation conditions.

Excessive nitrogen application leads to substantial nitrate accumulation in soil, increasing leaching risks. Previous studies have shown that soil nitrate content in various layers generally increases with nitrogen rate in maize production[25]. Under rainfed conditions in the North China Plain, strong soil nitrogen mineralization and nitrification result in large amounts of surplus nitrogen accumulating primarily as NO -N. This becomes a major nitrogen loss pathway when leached out of the root zone during concentrated rainfall or irrigation events[24-25]. Xu et al., using ^{1} N labeling, found that soil nitrate content at 250 kg · hm ^{2} nitrogen was significantly higher than at 180 kg · hm ^{2}, with significantly increased deep soil nitrate indicating downward leaching trends[22]. Our study showed that under drip fertigation in 2014, nitrate content at the same soil depth increased with nitrogen rate, with the highest content in the 0–20 cm layer and decreasing nitrate content with depth across all treatments. In 2015, nitrate content among treatments at the same depth showed similar trends to 2014, but vertical distribution varied by nitrogen rate. At 0–120 kg · hm ^{2}, changes among soil layers were minor, but at 240–360 kg · hm ^{2}, nitrate content in the 60–100 cm layer increased substantially with depth. In summary, excessive nitrogen application in the first year of drip-fertigated summer maize did not cause nitrate leaching under seasonal rainfall of 249 mm, but in the second year, excessive nitrogen caused obvious downward leaching under seasonal rainfall of 329 mm. Therefore, appropriate nitrogen rates reduce nitrate leaching under rainfall influence, achieving fertilizer savings, efficiency improvements, and environmental protection goals.

Due to inter-annual variations in rainfall, light, and temperature during different maize growth stages, nitrogen use efficiency and nitrate leaching are affected. Therefore, further research is needed on the effects of nitrogen rate on nitrate movement below 100 cm depth across different years in this region.

4 Conclusion

Based on two years of experimental results, under the soil fertility conditions of this study, nitrogen accumulation at different growth stages generally increased with nitrogen application rate under integrated water-fertilizer management, but the incremental effect diminished when nitrogen rates exceeded 120 kg · hm ^{2}. Post-harvest soil NO -N accumulation increased with nitrogen rate, with accumulation observed at the 1 m depth when nitrogen application exceeded 240 kg N · hm ^{2}. Considering grain yield, nitrogen use efficiency, and soil nitrate-N content comprehensively, the economically optimal nitrogen rate for summer maize under drip fertigation in the piedmont plain of North China is 174–187 kg · hm ^{2}.

References

[1] Qian Y, Zhang Z J, Fei Y H, et al. Sustainable exploitable potential of shallow groundwater in the North China Plain[J]. Chinese Journal of Eco-Agriculture, 2014, 22(8): 890-897.

[2] Gao Y S, Sun Y Y, Liu F M, et al. Research progress on integrated drip fertigation technology for maize under plastic film[J]. Journal of Maize Sciences, 2016, 24(6): 155-159.

[3] Oppong D E, Abenney M S, Sabi E B. et al. Effect of different fertilization and irrigation methods on nitrogen uptake, intercepted radiation and yield of okra (Abelmoschus esculentum L.) grown in the Keta Sand Spit of Southeast Ghana[J]. Agricultural Water Management, 2015, 147(2): 34-42.

[4] Yang Xiaohong, Yan Chengming, Zhang Jiangzhou, et al. Analysis of advantages, disadvantages, and development strategies of fertigation technology in China[J]. Journal of Agriculture, 2014, 4(1): 76-80.

[5] Tanaskovik V, Cukaliev O, Romic D, et al. The influence of drip fertigation on water use efficiency in tomato crop production[J]. Agriculturae Conspectus scientificus, 2011, 76(1): 57-63.

[6] Agostini F, Tei F, Silgram M, et al. Decreasing nitrate leaching in vegetable crops with better N management [C]//Lichtfouse E. Engineering, Biofertilisation, Soil Quality and Organic Farming. Springer Press, 2010: 147-200.

[7] Thompson R B, Martinez-Gaitan C, Gallardo M, et al. Identification of irrigation and N management practices that contribute to nitrate leaching loss from an intensive vegetable production system by use of a comprehensive survey[J]. Agricultural Water Management, 2007, 89(3): 261-274.

[8] Guo B Y, Gao H, Tang C, et al. Effects of water-nitrogen coupling on nitrogen uptake, water and nitrogen use efficiency, and yield of drip-irrigated maize[J]. Chinese Journal of Applied Ecology, 2015, 26(12): 3679-3686.

[9] Wang L M, Ye Y L, Chen F J, et al. Effects of nitrogen fertilization on yield and nitrogen efficiency of different maize varieties[J]. Chinese Journal of Eco-Agriculture, 2012, 20(5): 529-535.

[10] Wang Y, Feng G Z, Zhang T S, et al. Effects of mixed application of controlled-release N fertilizer and common urea on grain yield, N uptake and soil N balance in continuous spring maize Production[J]. Scientia Agricultura Sinica, 2016, 49(3): 518-528.

[11] Zhang J T, Wang Z M, Zhou S L. Soil Nitrate N Accumulation Under Different N-Fertilizer Rates in Summer Maize and Its Residual Effects on Subsequent Winter Wheat[J]. Scientia Agricultura Sinica, 2013, 46(6): 1182-1190.

[12] Chang J F, Dong P F, Zhang H H, et al. Effects of row spacing configuration on nitrogen uptake, utilization, and yield of summer maize[J]. Chinese Journal of Eco-Agriculture, 2016, 24(7): 853-863.

[13] Peng Y F, Yu P, Zhang Y, et al. Temporal and spatial dynamics in root length density of field-grown maize and NPK in the soil profile[J]. Field Crops Research, 2012, 131: 9-16.

[14] Jiang W S, Wang K J, Wu Q P, et al. Effects of narrow plant spacing on root distribution and physiological nitrogen use efficiency in summer maize[J]. The Crop Journal, 2013, 1(1): 77-83.

[15] Ye D J, Gao Q, He W T, et al. Effect of N application on N utilization and N balance in spring maize[J]. Plant Nutrition and Fertilizer Science, 2010, 16(3): 552- (incomplete reference).

[16] Zhang J T, Liu Y P, Li X H, Dynamic responses of nitrogen accumulation and remobilization in summer maize organs to nitrogen fertilizer[J]. Acta

Agronomica Sinica, 2013, 39(3): 506-514.

[17] Ji L, Zhang X Z, Li T X. Establishing Fertilization Recommendation Index of Paddy Soil Based on the "3414" Field Experiments in the Middle of Sichuan Hilly Regions[J]. Scientia Agricultura Sinica, 2011, 44(1): 84-92.

[18] Wang Y L, Liu T X, Tan J F, Zhang X, Li C H. Effect of N fertilization on yield, N absorption and utilization of two species of super high-yielding summer maize[J]. Agricultural Science Technology, 2012, 13: 339-342.

[19] Schmidt J, Beegle D, Zhu Q, et al. Improving in-season nitrogen recommendations for maize using an active sensor[J]. Field Crops Res, 2011, 120: 94-101.

[20] Chen Y, Xiao C, Wu D, et al. Effects of nitrogen application rate on grain yield and grain nitrogen concentration in two maize hybrids with contrasting nitrogen remobilization efficiency[J]. European Journal of Agronomy, 2015, 62(62): 79-89.

[21] Jing L Q, Zhao F C, Liu P, et al. Effects of Nitrogen Treatments on Dry Matter Production and Photosynthetic Characteristics of Summer Maize (Zea mays L) under Super-high Yield Conditions[J]. Journal of Nuclear Agricultural Sciences, 2014, 28(2): (incomplete reference).

[22] Xu M J, Zhang L, Wang X Y, et al. Effects of different management patterns on uptake, distribution and fate of nitrogen in summer maize[J]. Journal of Plant Nutrition and Fertilizer, 2015, 21(1): 36-45.

[23] Jin L B, Cui H Y, Li B, et al. Effects of Integrated Agronomic Practices on Nitrogen Efficiency and Soil Nitrate Nitrogen of Summer Maize[J]. Acta Agronomica Sinica, 2013, 39(11): 2009-2015.

[24] Zhao R F, Chen X P, Zhang F S. Nitrogen cycling and balance in winter wheat-summer maize rotation system in Northern China Plain[J]. Acta Pedologica Sinica, 2009, 46(4): 684-687.

[25] Ju X T, Liu X J, Zhang F S. Study on effect of nitrogen fertilizer and nitrogen balance in winter wheat and summer maize rotation system[J]. Scientia Agricultura Sinica, 2002, 35(11): 1361-1368.

Note: Figure translations are in progress. See original paper for figures.

Source: ChinaXiv —Machine translation. Verify with original.