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RESEARCH

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Effect of different fertilization managements on nitrate accumulation in a Mollisol of Northeast China

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Abstract

Background: In a continuous spring maize system in Northeast China, the accumulation and succession characteristics of nitrate in Mollisol with four fertilization treatments, including no fertilization (CK), farmers' conventional fertilization (FC), recommendation fertilization (RF), and controlled release fertilizer application (CRF), were compared over a 6-year field plot trial.

Results: On average, the RF and CRF treatments decreased nitrate nitrogen by 16.6 and 39.5 % in the 0–90 cm soil layer, respectively, and maintained a relatively high maize grain yield, as compared to the FC treatment. The accumulation of nitrate nitrogen was more obvious in the CRF treatment compared with the other fertilizer treatments under the arid climate. However, the high precipitation resulted in the leaching of nitrate nitrogen into the deeper soil layer in all the fertilizer treatments. The maximum of nitrate nitrogen in the 0–90 cm soil layer was 81.4 kg N/ha at a nitrogen fertilizer rate of 250 kg N/ha in the long-term trial, which was within the rational and safe level for groundwater.

Conclusions: The best fertilization strategy to decrease nitrate accumulation in soil should consider both soil characteristics and precipitation.

Keywords: Nitrate, Recommendation fertilization, Controlled release fertilizer, Long-term experiment

Background

Maize is a major cereal crop worldwide and accounts for over 35 % of global food production. China, as one of the golden maize belts in the world, is the second largest maize-producing country, with a total growing area of 3.05 × 10^7 ha recorded in 2009 [8], which was mainly concentrated in North, Northeast, and Southwest China [26]. The spring maize zone of Northeast China is one of the most important areas of food production in China, and maize yield from this region has reached 35 % of the total maize production in China [37, 39]. Nitrogen is one of the main plant nutrients and is essential for effective plant growth [36]. Maize, as a high-yield crop, is frequently applied with amounts of N fertilizer. The contamination of surface and groundwater by nitrate accumulation in soil is a major environmental concern in China. The reason could be due to the excessive nitrogen fertilizer application, especially over the past two decades. In Northeast China, in 2012, 10.7 million hectares of land were cultivated with maize [28]. The increasing application rate of N fertilizer had no discernible increase on yield parameters, which however resulted in substantial N volatilization and N residues in soils [15, 18, 29].

Loepez-Bellido et al. [19] reported that in a typical rainfed area of southern Spain, the nitrate nitrogen residue in soil increased with time, accumulated mostly in the 30–60 cm soil layer, and additionally the average nitrate residue was 82, 88, 116 and 145 kg N/ha in the 0–90 cm soil layer at the N rates of 0, 50, 100 and 150 kg N/ha, respectively. Wang [35] analyzed more than 800 records in 120 papers published over the last 30 years concerning nitrate accumulation in soils in China and reported that this phenomenon peaked at 200 kg N/ha in 0–100 cm soil layer as the average for field crops such as maize,

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wheat, and rice in China and even 700 kg N/ha in vegetable crops. Kou et al. [16] noted that nitrate accumulation in the 0–90 cm soil layer was 221–275 kg N/ha for the wheat–maize rotation system in North China. However, Roth and Fox [25] reported that the residue of soil nitrate ranged from 41 to 138 kg N/ha in 0–120 cm after harvesting a maize crop which was fertilized by economic N rate.

Regarding ecosystems and from an ecological standpoint, the negative effects of nitrate residues can be reduced by studying the efficiency of N fertilizer in soil [20]. On the basis of crop plants, N efficiency was affected by applying different N fertilizer rates and by adjusting the timing of fertilizer application [1, 45]. Gao et al. [10] reported that on average, the nitrogen application rate was 207 kg/ha in Northeast China, and 220 kg/ha in the central zone of Jilin Province in the continuous spring maize system in 2008; furthermore, the phenomenon of excessive nitrogen application (N >240 kg/ha) reached 40 %. Over-application of N fertilizer has become a common practice in maize production systems and has led to nutrient imbalances and inefficient fertilizer applications, and has resulted in negatively impacting the environment [3, 15]. Soil testing has been developed as a means of improving fertilizer use efficiency in China. He et al. [12] conducted multiple-point field trials based on soil testing in North Central China and showed that soil test-based fertilizer recommendations could increase wheat and maize yield and improve fertilizer use efficiency. Furthermore, controlled release fertilizer technologies, by regulating the time of N release from fertilizers, has the potential to reduce leaching losses of nitrate in soil [14, 27, 30, 31]. Many studies have found that the application of controlled release N fertilizer significantly increased the NUE and yields of crops [11, 40]. Zhang et al. [42] reported that the yields of both rice and oilseed rape with applied CRU increased by 6.9 % each, even when the CRU rate was reduced by 20 % relative to common urea. Dinnes et al. [6] reported that splitting fertilization could reduce the losses of nitrates from crop plants. The European Union recommends that control should be exercised over the amount of fertilizer applied; however, they do not specify limits the safe amount of fertilizer applied depends on climatic conditions, the nitrogen absorption capacity of crops, the soil N content as well as the frequency and timing of the application [2].

Many studies have reported that excessive N input resulted in higher nitrate nitrogen residues in soil [4, 32]. However, information on nitrate accumulation in soil, based on reducing the nitrogen rate and controlled release fertilizer ensuring yield, is still scarce in Northeast China. Therefore, the objectives of this 6-year field research in Northeast China were to evaluate the effects of reduced nitrogen rate and controlled release fertilizer (1) on maize yield and N uptake, (2) on nitrate accumulation in soil, and (3) on nitrate movement in different soil profiles.

Methods

Site description and experimental design

The field trials were conducted from 2004 to 2009 in a Mollisol in Dehui (DH) city, Jilin Province, Northeast China (44°33′N, 125°43′E). The climate is characterized by a temperate continental monsoon. The contents of soil organic matter, total N, Olsen phosphorus (P), and available potassium (K) in the upper 30-cm soil layer were 34 g/kg, 2.62 g/kg, 41.3 mg/kg and 172.9 mg/kg, respectively. Nitrate nitrogen in the 0–90 cm soil layer was 38.2 mg/kg, while the pH was 7.4.

The trial sites were cultivated with continuous spring maize planted from May to October each year for a duration of 6 years. Four nitrogen fertilization management treatments (NMTs) were conducted in a randomized block design with four replications, namely block treatment with no nitrogen fertilizer (CK), farmer conventional treatment with chemical fertilizer—urea by splitting fertilization (FC) and applying high N rate (which was applied in more than 40 % of farmers' fields in Dehui county), recommendation fertilization treatment with low N rate in which the N rate was calculated by soil testing and yield target (RF), and finally controlled release fertilizer (CRF) which is a mixture of common urea and 4-month longevity of the polymer coating of sulfur-coated urea (hybrid coatings with sulfur and a thin polymer coating containing 35 % N, made by Luyue chemical Co. Ltd., Shandong, China); the N ratio was 1:2. Nitrogen release rate of polymer-coated urea in 25 °C water is shown in Fig. 1. The nitrogen fertilizer rate of CRF treatment was 20 % less than that of FC treatment. Eighty N kg/ha of the nitrogen fertilizer, and all phosphorus, potassium fertilizer in FC and RF treatments and all NPK fertilizers in CRF treatment were uniformly plowed into the soil before broadcasting, and other fertilizers as top-dressing were applied between the V6 and V7 stages. Phosphorus and potassium fertilizers were triple superphosphate (P 46 %) and potassium chloride (K 60 %), respectively. The four treatments were administered by the local farmers' traditional planting practices which included planting density, sowing, and the harvest time, as well as fertilizer application periods. Each plot was 10 m × 4 m with 6 rows of maize spaced 0.66 m apart. Nitrogen, phosphorus, and potassium fertilizer rates of each treatment are shown in Table 1. The same and typical spring maize hybrids in each year in Northeast China were used. Plant density each year was 55,000 plants/ha. The 6-year trial was conducted under rain-fed condition.

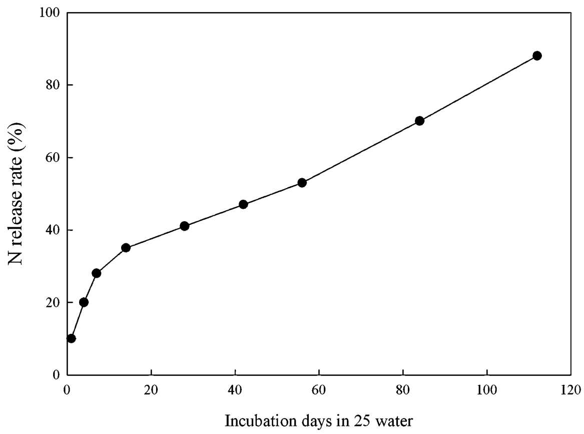

Fig. 1 N accumulative release curve of control release fertilizer

Table 1 Fertilizer rate and fertilization information of different treatments

Treatment	N (kg/ha)	P_2O_5 (kg/ha)	K_2O (kg/ha)	Fertilization
CK	0	70	60	Basal fertilization
FC	250	70	60	Splitting fertilization
RF	210	70	60	Splitting fertilization
CRF	156	70	60	Single fertilization

The management of pests, diseases, and weeds in each treatment was well controlled by farm managers.

Soil sampling and analysis

In each plot, four cores with 0.9 m depth were pooled to obtain a representative soil sample, homogenized, and passed through a 0.5-mm-diameter sieve. The nitrate contents from three soil layers (0–30, 30–60 and 60–90 cm depths) in each year were determined by extraction using 1 M KCl at a 1:10 ratio (Continuous-Flow Analysis-AA3 analyzer, Seal, Germany).

Statistics analysis

Statistical analysis was conducted with mixed analysis of variance (SAS software 2004) at the 5 % significance level.

Climate background

Monthly rainfall, hours of sunshine, and average Max/Min temperatures during the growing season (May–September) from 2004 to 2009 are shown in Fig. 2. Rainfall patterns experienced during the trial were different across years with heavy rainfalls recorded in 2008 and relative drought periods recorded in 2004, 2007 and 2009. The average annual rainfall in Dehui City, Northeast China, was 520 mm, and 80 % of the total rainfall occurred during May to September, which is the period during which maize requires the highest amount of water for germination. Rainfall in 2008 exceeded 50 % of the average annual precipitation; and the rainfall in 2004, 2007 and 2009 was 15–20 % less than normal.

Results

Yield and N uptake

Different treatments had significant differences in the yield and N uptake rates. For yield (Table 2), there was no significant difference for the fertilizer treatments in the 6-year field trials except for CK treatment. According to the statistical data, reduction of the nitrogen fertilizer rates (RF) and single fertilizer applications (CRF) had no effect on yield. In relation to nitrogen uptake (Table 3), the nitrogen uptake rates for the nitrogen fertilizer application treatments showed no significant differences in the long-term field trials. In the first year, there were no significant differences among the CK, FC, and RF levels, which was possibly due to the high soil fertility in Mollisol. The parameters of time, treatments, and their interactions significantly affected the yield and nitrogen uptake of maize (Table 4).

Nitrate concentration in 0–90 cm soil layer

Time and treatments were the main contributing factors for nitrate accumulation in soil (Table 4). In Fig. 3, with the increasing rainfall, it was seen that rainfall and nitrate accumulation had no direct correlation; however, nitrogen uptake had significant correlation with rainfall.

The amount of accumulative nitrates in the soil profile (0–90 cm) across the years is depicted in Fig. 4. Soil nitrogen nitrates of fertilizer treatments were remarkably higher than those of the CK treatment, which implied that nitrogen fertilizer application increased the nitrate content in soil. Regarding the CK treatment, nitrate accumulation rates post-harvest in the successive 6-year field trials were lower than those before the broadcast, which resulted in nitrogen deficiency in soils. Nitrate residue peak in the 0–90 cm soil layer was 81.44 N kg/ha by 250 N addition in long-term studies. Recommendation fertilizer rate (RF) and controlled release fertilizer (CRF) could decrease nitrate nitrogen in the 0–90 cm soil layer on average by 16.6 and 39.5 %, respectively, compared with the farmer conventional fertilizer (FC). A mitigating factor for the higher nitrate content of the CRF treatment recorded in 2004 was the increased hours of sunshine and poor rainfall throughout the year. The obvious lower rainfall in the rain-fed maize system impeded the release of CRF, which resulted in relatively higher nitrogen residues in the soil.

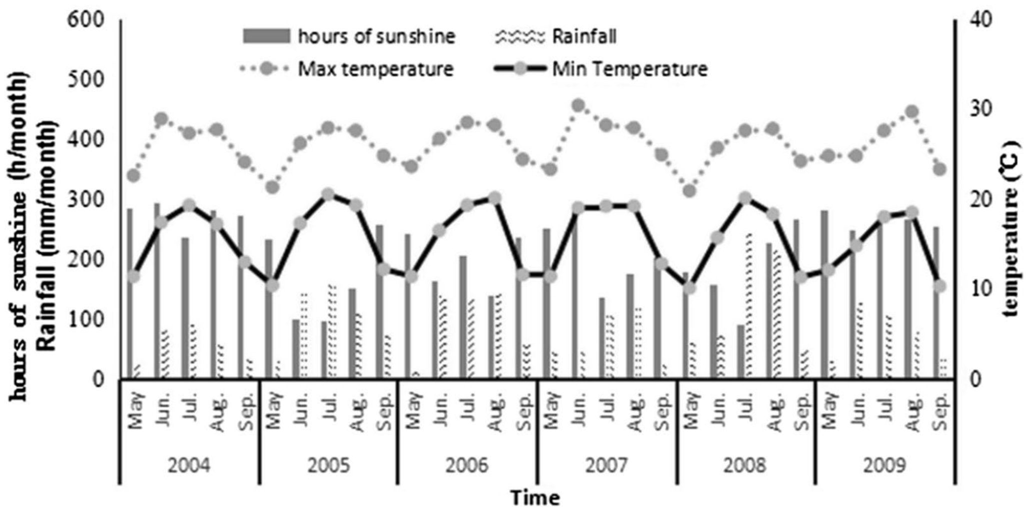

Fig. 2 Monthly rainfall (mm), hours of sunshine, and averaged Max/Min temperature during the growing season (May–September) from 2004 to 2009

Table 2 Average yields of different treatments during 2004–2009

Year	CK	FC	RF	CRF
2004	7.2 ± 1.0b	9.2 ± 0.8a	9.2 ± 0.5a	8.9 ± 0.9a
2005	6.8 ± 1.4b	10.9 ± 0.5a	10.0 ± 0.5a	10.9 ± 0.5a
2006	4.2 ± 0.8b	13.6 ± 0.7a	13.7 ± 0.7a	13.6 ± 0.9a
2007	4.3 ± 0.4b	10.8 ± 0.9a	10.5 ± 0.8a	10.6 ± 0.9a
2008	5.5 ± 0.6b	10.2 ± 1.6a	11.1 ± 0.8a	10.9 ± 0.6a
2009	4.8 ± 0.8b	9.7 ± 0.6a	10.4 ± 0.8a	10.0 ± 0.5a

Mean values in each line in the same year followed by different letters are significantly different at the 0.05 level

Table 3 Nitrogen uptake of different treatments during 2004–2009

Year	CK	FC	RF	CRF
2004	129.8 ± 28.5b	190.5 ± 60.1ab	178.8 ± 32.2ab	203.2 ± 30.1a
2005	143.7 ± 24b	200.4 ± 42.3a	221.9 ± 23.3a	192.5 ± 24.5a
2006	61.6 ± 9.0b	217.7 ± 20.8a	226.5 ± 11.8a	227.8 ± 18.2a
2007	38.4 ± 8.8b	164.8 ± 33.4a	164.2 ± 5.1a	145.0 ± 10.4a
2008	86.2 ± 11.5b	225.0 ± 19.3a	259.2 ± 19.3a	248.5 ± 25.9a
2009	55.0 ± 12.0b	153.4 ± 17.6a	202.0 ± 34.9a	134.4 ± 9.7a

Mean values in each line in the same year followed by different letters are significantly different at the 0.05 level

Table 4 Analysis of variance (mean squares) of the soil nitrate content at harvesting, yield, and N uptake affected by years and fertilization managements

Source	*df*	Mean square
Yield (kg ha^{-1})		
Year (Y)	5	14,969,990.7**
Treatment (T)	3	169,835,958**
Y × T	15	6,715,569.4**
N uptake (kg ha^{-1})		
Year (Y)	5	15,038.9**
Treatment (T)	3	76,425.2**
Y × T	15	2776.9**
Nitrate content (0–90 cm)(kg ha^{-1})		
Year (Y)	5	1399.41**
Treatment (T)	3	8843.44**
Y × T	15	392.20**

** Significant at the 0.01 probability level

Nitrate changes of different treatments in soil profile

From nitrate dynamic changes in the 6-year field trial (Fig. 5), it can be seen that nitrate content in the 0–30 cm soil profile was higher than those in the other profiles, especially for the FC and RF treatments. The main reason for the higher nitrate content in the surface soil was the top-dressing applied in the jointing stage, which increased the nitrate accumulation in topsoil when compared with the single fertilization treatment. However, the accumulated nitrate was lower in 2004 and 2007, and this phenomenon was possibly due to high temperature and shortage of rainfall. This resulted in ammonia volatilization loss by denitrification and perpetuated potential environmental risks.

At the 30–60 cm soil layer, nitrate accumulation ranged from 0.96 kg N/ha (CK treatment in 2004) to 27.91 kg N/ha (FC treatment in 2008). Furthermore, soil nitrate

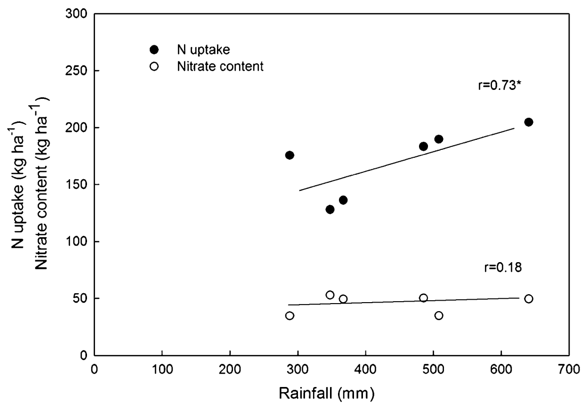

Fig. 3 Correlation analysis between rainfall and N uptake as well as nitrate content. *Significant at the 0.05 probability level

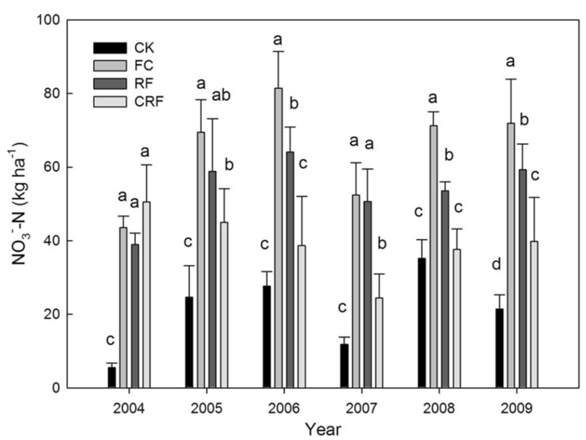

Fig. 4 Nitrate content in the soil profile (0–90 cm) for 6 years experiment in Northeast China

levels increased significantly in 2008, which is possibly related to extensive water movement during heavy rainfall periods, causing more N to leach deeper into the soil layers.

At the 60–90 cm soil layer, nitrate accumulation had a direct proportionality with time, increasing in trend as the years increased.

Discussion

In Northeast China, the use of single basal fertilization has increased in trend due to labor cost increasing exponentially [33, 34]; however, splitting fertilizer technology could increase the efficiency of fertilizer. Gao et al. [9] reported that in the maize belt in Jilin Province, plant areas of single fertilization already amounted to 62.5 % of the total planted areas. Controlled release fertilizer, as a new single fertilization, not only minimized labor costs in farming systems [21], maintained the levels of nutrients over a relatively longer period, and increased nitrogen use efficiency [7], but also significantly reduced the nitrate accumulation when compared with the traditional fertilizer (Urea). Consequently, this study has similar results to and concurs with several other studies performed previously [5, 38].

The excessive application of N fertilizer is a common practice for ensuring maximum yields in maize planting systems in Northeast China. But Miao et al. [23] reported that by increasing cumulative nitrate N amounts, the seed yields and percentages increased by N addition rapidly declined, and when the cumulative nitrate amount was over 250 N kg/ha, there was no significant yield increase. In this trial, reducing fertilization treatment (RF) could work in harmony with the demand of crop as well as decrease nitrate accumulation risks.

Some researches in China showed that the concentration of nitrate residues in the 0–90 cm soils increased significantly with nitrogen application rates [17, 44]. Malhi et al. [22] surmised that the concentration of nitrate residue in soils was boosted by nitrogen application and could leach into the 90-cm soil profile; conversely, by controlling the application of nitrogen, having no tillage and performing straw returning, this could control the accumulation of nitrogen in the soil profile. The results of this study showed that nitrate accumulation in the 0–90 cm soil profile in Northeast China ranged from 5.54 to 81.44 N kg/ha, and averagely 56 N kg/ha which was only 50 % of the average value in Chinese farmlands [24]. The average nitrate accumulation in North China and South China was 120 kg/ha and 133 kg/ha, respectively [24]. In European Union, the residue N_{min} was limited to lower than 90 kg/ha in many countries [13]. In North China, Zhong et al. [43] suggested that the suitable residue N_{min} was an advantage of N absorption and utilization by the successive crop; however, they further added that residue levels should not exceed 150 kg/ha in the winter wheat–summer maize rotation crop zone with high-yield and environmental protection. Therefore, in the continuous maize system in Northeast China, presently nitrate accumulation was within the rational levels. Furthermore, by reducing both the long-term fertilizer rate and controlled release fertilizer, the effect of fertilizer control was remarkable.

The amount of irrigation and rainfall influenced the nitrate accumulation peak in soil profiles. The analysis of the relationship between nitrate accumulation peak depth and rainfall in rain-fed agricultural regions with yearly 400–800 cm of rainfall was reported by Zhang [41]. The authors noted that there was a positive correlation between the peak depth of nitrate and rainfall; furthermore, peak depth focused on the 80–200 cm soil layer. A large of nitrate in soils would be leached to deeper soil

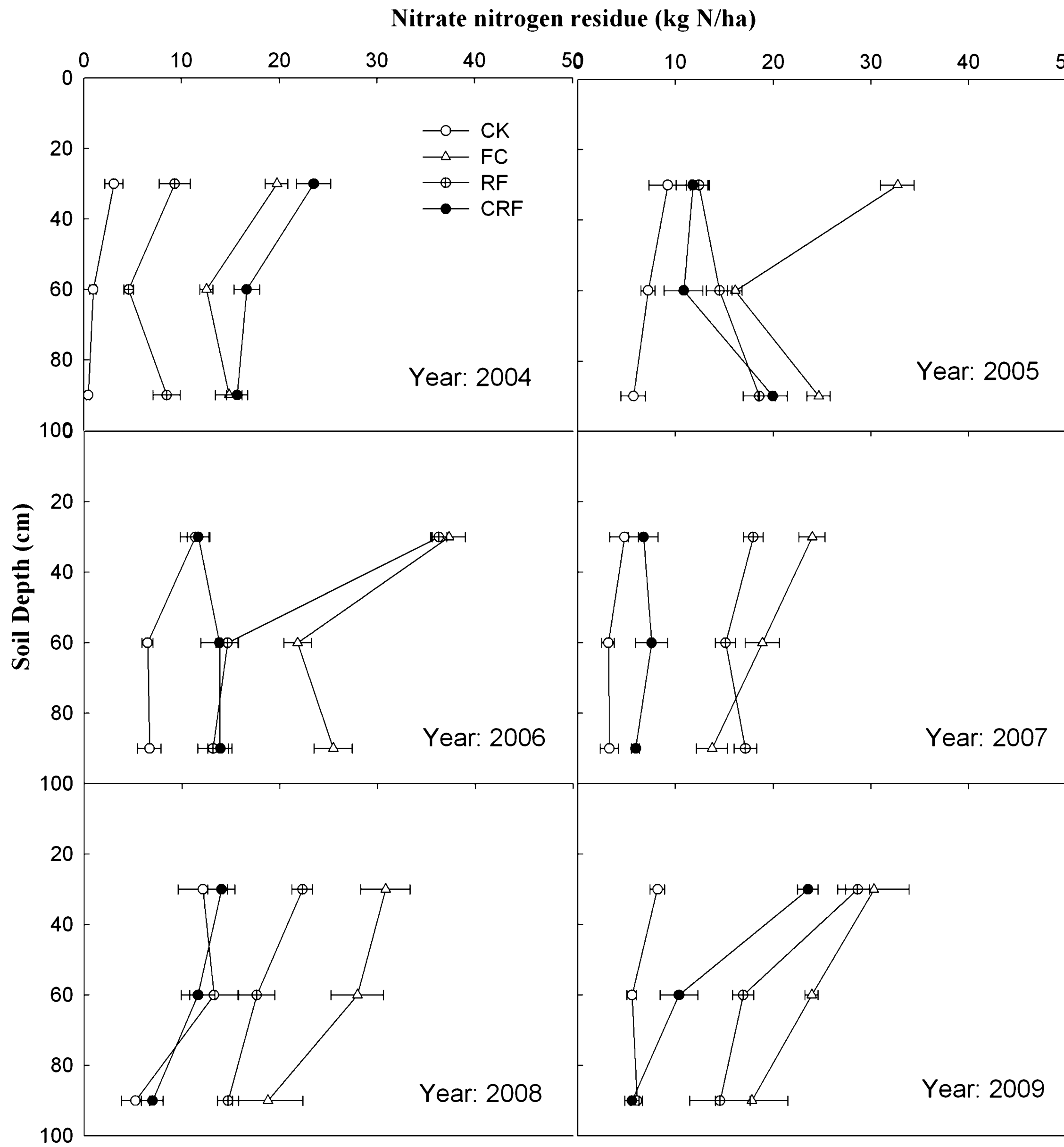

Fig. 5 Effect of different fertilization modes on yearly nitrate accumulation in different soil profiles (0–30, 30–60, 60–90 cm) in Northeast China. *Error bars* indicate the standard errors of mean (SE)

profile during periods of rainstorms and intense irrigation. Therefore, based on the above, it can be deduced that in this study there was a large possibility of the presence of nitrates in the deeper soil profiles.

Conclusion

Cumulative nitrate nitrogen in the 0–90 cm soil layer was associated with the application of nitrogen and precipitation in the rain-fed maize planting system. On average, the RF and CRF treatments decreased nitrate nitrogen by 16.6 and 39.5 % in the 0–90 cm soil layer, respectively, and maintained a relatively high maize grain yield, when compared with the FC treatment. Under the arid climate, the application of controlled release fertilizer increased the accumulation of nitrate in soils due to a restraint in release. However, the high precipitation resulted in the leaching of nitrate into the deeper soil layer. The maximum of nitrate nitrogen in the 0–90 cm soil layer was 81.4 kg N/ha at a nitrogen fertilizer rate of 250 kg N/ha in the long-term trial, which was within the rational and safe levels for groundwater. Therefore, the best fertilization strategy to decrease nitrate accumulation in soil should consider both soil characteristics and precipitation.

Authors' contributions

LY and ZZ carried out the analysis of yield and nitrate changes, AMA analyzed the effect factors of nitrate, all steps were supervised by JZ and QG. All authors read and approved the final manuscript.

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Competing interests

The authors declare that they have no competing interests.

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