Environmental Pollution 268 (2021) 115004

Contents lists available at ScienceDirect

Environmental Pollution

journal homepage: www.elsevier.com/locate/envpol

Invited paper

Identifying the critical nitrogen fertilizer rate for optimum yield and minimum nitrate leaching in a typical field radish cropping system in China☆

Jiajia Zhang [a], Ping He [a, *], Wencheng Ding [a], Sami Ullah [a], Tanveer Abbas [a], Mingyue Li [b], Chao Ai [a], Wei Zhou [a]

[a] *Ministry of Agriculture Key Laboratory of Plant Nutrition and Fertilizer, Institute of Agricultural Resources and Regional Planning, Chinese Academy of Agricultural Sciences (CAAS), Beijing, 100081, China*

[b] *Tianjin Institute of Agricultural Resources and Environment, Tianjin, 300192, China*

ARTICLE INFO

Article history:
Received 28 March 2020
Received in revised form
13 May 2020
Accepted 7 June 2020
Available online xxx

Keywords:
Radish yield
Nitrate residue
Nitrogen use efficiency
Nitrate leaching
Critical nitrogen application rate

ABSTRACT

Nitrate leaching caused by overusing or misusing nitrogen (N) fertilizers in field vegetable cropping systems in China is a leading contributor to nitrate contamination of groundwater. Identification of the critical fertilizer N input rate could support management decisions that maintain yields while reducing the impact of nitrate leaching on groundwater. A four-season field experiment involving six N treatments (0, 60, 120, 180, 240, and 300 kg N ha^{-1}) was undertaken to investigate the impacts of various N rates on N use efficiency (NUE), seasonal nitrate leaching loss (SNLL), nitrate residue (NR), and radish yield, and to identify the critical N fertilizer rate for both optimum yield and minimum nitrate leaching loss in a field vegetable (radish, *Raphanus sativus* L.) cropping system in northern China. The results showed that radish yield enhanced quadratically and NUE reduced linearly with increasing N addition, while the NR and SNLL increased exponentially. The yield did not increase markedly when N fertilization exceeded 180 kg N ha^{-1}. SNLL and nitrate concentrations in the leachate averaged 11.5–71.5 kg N ha^{-1} and 5.1–35.6 mg N L^{-1}, respectively, under N rates of 60–300 kg N ha^{-1}. The results showed that N fertilizer rate ranging from 180 to 196 kg N ha^{-1} resulted in high yields and low nitrate leaching losses. Compared with those in response to the N fertilizer amount applied by local farmers, the NUE, NR, and SNLL in response to the N fertilizer amount identified in this study increased, decreased by 30.9%–35.0%, and decreased by 49.9%–55.7%, respectively, without any yield loss. Thus, a critical N fertilizer rate ranging from 180 to 196 kg N ha^{-1} is recommended to obtain optimum yields with minimal environmental risks in radish fields in northern China.

Main findings: We determined that the critical N fertilizer rate for optimal radish yields and minimal nitrate leaching losses is 180–196 kg N ha^{-1}.

1. Introduction

Vegetables, as rich sources of dietary fibers, vitamins, trace minerals, and antioxidants, are immensely valued in the human diet (Sahu, 2004). Nitrogen (N) fertilization is necessary for the production of field vegetables to ensure ample yields and excellent quality (Zhang et al., 2015a; Tilman et al., 2002). However, vegetable growers often try to maximize yields by adding excessive amounts of inorganic N and by applying excessive amounts of irrigation (Zhao et al., 2010; Zhu et al., 2005; Chen et al., 2004). However, large N fertilizer inputs may not substantially benefit on crop yields; rather, they may significantly reduce nitrogen use efficiency (NUE) and jeopardize the environment (Huang et al., 2017; Song et al., 2009). Studies have showed that single-season N fertilizer inputs was more than 300 kg N ha^{-1} in some vegetable cultivation areas in northern China; this amount is almost twice that required by most vegetable crops (Zhang, 2005), resulting in an NUE of only 33% (Song et al., 2009). Excessive amounts of N fertilizer applied to fields also results in the buildup of a substantial

☆ This paper has been recommended for acceptance by Yong Sik Ok.

* Corresponding author.
E-mail addresses: heping02@caas.cn (P. He), zhouwei02@caas.cn (W. Zhou).

https://doi.org/10.1016/j.envpol.2020.115004
0269-7491/

amount of nitrate within the soil profile (Shi et al., 2009). Residual nitrate in the soil is susceptible to leaching into deep soil layers because of the high mobility of nitrate, high permeability of the soil, low capacity of cation exchange, shallow root systems of vegetables, and high amounts of irrigation or precipitation (Zhang et al., 2017; Qafoku, 2014).

Nitrate leaching has caused numerous concerns from both the scientific community and the public because of the resulting decline in NUE and, more importantly, the resulting contamination of groundwater (Padilla et al., 2018; Kaushal et al., 2011; Agostini et al., 2010). The World Health Organization (WHO) and European Union have set a limitation of 11.3 mg NO_3^--N L^{-1} of groundwater to protect human health and the environment (European Commission, 1999). In addition, numerous European countries have successfully enacted legislation to control the N balance at the farmland scales to mitigate nitrate contamination of ground water (Eichler and Schulz, 1998). However, within farming communities in China, nitrate leaching is much less of a concern than is increasing yields. Recently, with the increase in chemical N fertilizer rates in arable land, nitrate leaching problems in southern China have been well recognized; these problems have shown to be related mainly to high amounts of rainfall, increased amounts of irrigation applied and N inputs (Shi et al., 2009; Min et al., 2012). Nitrate leaching has been underestimated or even neglected for decades in northern China because of the scarce precipitation in this area. However, nitrate contamination of groundwater in this region is rapidly increasing (Yang et al., 2015; Ju et al., 2004). A field survey carried out in multiple provinces in northern China indicated that approximately half of 600 groundwater samples surpassed the WHO drinking water standard (Ju et al., 2006). In addition, Zhao et al. (2007) measured the nitrate pollution of 1139 groundwater samples (including those from grain fields, vegetable fields, and orchards) in North China and showed that more than 34% of samples surpassed the WHO standard, of which those from vegetable fields were the most affected. Drinking water in the North China Plain is sourced exclusively from groundwater sources; therefore, it is important to keep the nitrate concentration below the maximum allowed contamination level. Some studies have investigated nitrate leaching in North China, and most of them have focused on grain crops or greenhouse vegetable cropping systems (Dong et al., 2019; Zhang et al., 2015b; Zhu et al., 2005). However, there are no relevant reports on nitrate leaching in open field vegetable cropping systems. Thus, investigations of the detrimental effects of excess N fertilization on yield, NUE, and nitrate leaching in open field vegetable cropping systems are urgently needed. Moreover, it is also important to identify the most suitable N input rate to optimize yields and minimize nitrate leaching losses in field vegetable cropping systems.

Radish (*Raphanus sativus* L.) is an important vegetable worldwide. Radish is the second most cultivated vegetable in China in terms of planting area and total production (FAO, 2017) and is typically grown in the field during spring and autumn in northern China; for those reasons, radish was selected for the present study. Radish growers typically apply large amounts of N fertilizer, up to 300 kg N ha^{-1} $season^{-1}$, and high amounts of irrigation to maximize yields (Huang et al., 2017). These measures create conditions that can be conducive to nitrate leaching. We hypothesized that there is a specific N fertilizer rate or range to minimize the nitrate leaching losses while simultaneously ensuring high radish yields. Therefore, a four-season field trial involving multiple N fertilizer rates was conducted to (1) evaluate the effects of different N application amounts on radish yields and NUE; (2) investigate the responses of nitrate residue, leaching, and leaching factors to increased N fertilizer rates; and (3) identify the critical N fertilizer input rate or range that can maintain crop yields together with a high NUE while minimizing undesirable environmental impacts.

2. Materials and methods

2.1. Experimental site

A four-season stationary field experiment was undertaken at the experimental station (39.07 N, 116.88 E) of the Tianjin Academy of Agricultural Sciences from August 2017 to July 2019 in Wuqing district, Tianjin municipality, China. The experimental base is situated on the North China Plain, the area of which has a sub-humid temperate monsoon climate. The average annual air temperature, surface evaporation, and annual precipitation are 12 °C, 1778 mm, and 586 mm, respectively, and the average frost-free period is approximately 203 d per year. The daily precipitation and air temperature throughout the experiment are shown in Fig. 1. No extreme weather events occurred during the research period. The soil characteristics (0–20 cm) before the start of the experiment were as follows: soil texture, clay loam; bulk density, 1.29 g cm^{-3}; pH, 8.39; soil organic matter, 13.5 g kg^{-1}; total N content, 0.95 g kg^{-1}; NO_3–N content, 10.9 mg kg^{-1}; Olsen-P, 18.4 mg kg^{-1}; and available K, 309.0 mg kg^{-1}.

2.2. Experimental layout

Six N fertilizer treatments were tested in each of the autumn and spring cropping seasons. In each season, the experimental plots received 0, 60, 120, 180, 240, and 300 kg N ha^{-1}, represented as N0, N60, N120, N180, N240, and N300, respectively. The N300 treatment represents the rate used by farmers in radish production. The N180 treatment was determined according to the Nutrient Expert for Radish, a fertilization decision tool (Zhang et al., 2019a, 2019b). In each season, the phosphorus (P) and potassium (K) fertilizer inputs were 100 kg P_2O_5 ha^{-1} and 150 kg K_2O ha^{-1}, respectively; organic manure was not applied. A randomized complete design with three replicates was used. All P fertilizer and 60% of N and K fertilizers were applied uniformly as basal fertilizers before sowing, and the remaining N and K fertilizers were applied during the fleshy root expansion stage. Each plot was 30 m^2 (5 m long × 6 m wide), and there was a buffer zone of 1.5 m between blocks and 1 m between plots. The sources of the N, P, and K fertilizers were urea (46% N), single superphosphate (12% P_2O_5), and potassium sulfate (50% K_2O), respectively. The radish variety used is a common, locally used, high-yielding variety. The irrigation duration and amount were strictly maintained at uniform levels for all treatments, and the amount of irrigation applied was dependent on the status of crop growth, soil moisture, and weather conditions. Detailed information about the radish planting, irrigation, and fertilization in each season from 2017 to 2019 is listed in Table 1. Weeds were eradicated, and fungicide and insecticide were sprayed to control diseases and pests.

2.3. Sample analysis

At harvest, the fleshy roots and leaves of radish were harvested manually, and yields were measured separately for each season. Afterwards, ten plant samples were collected from each plot and then oven dried to a constant weight to measure their dry matter weight. The total N content in the fleshy roots and leaves was tested using the Kjeldahl method. The fleshy root yield of radish in each plot was recorded on a fresh weight basis. In each season, soil samples (0–1 m at 0.2 m increments; three cores per plot) were collected before sowing and after harvesting the crop and the fresh soil samples were extracted with calcium chloride. The extracts were immediately measured for NO_3^--N content via continuous

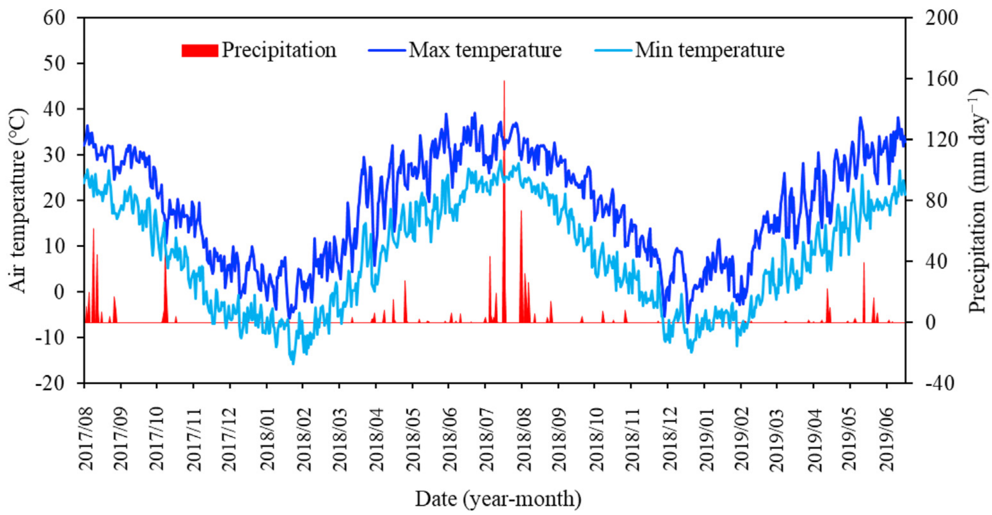

Fig. 1. Daily precipitation and maximum and minimum air temperature from August 2017 to June 2019.

Table 1
Tillage, planting, irrigation, and fertilization during each growing season from August 2017 to June 2019.

Management practice	Growing season			
	Autumn 2017	Spring 2018	Autumn 2018	Spring 2019
Radish cultivar	Baiyuchun			
Tillage date (m/d/y)	08/27/2017	04/16/2018	08/16/2018	04/06/2019
Sowing date (m/d/y)	08/29/2017	04/17/2018	08/20/2018	04/07/2019
Irrigation date (m/d/y) and depth (mm)	08/30/2017 (*93*)	04/17/2018 (*50*)	08/20/2018 (*80*)	04/08/2019 (*133*)
	09/09,/2017 (*117*)	05/19/2018 (*50*)	08/23/2018 (*67*)	04/16/2019 (*67*)
	09/20/2017 (*57*)	05/27/2018 (*57*)	09/08/2018 (*67*)	05/14/2019 (83)
	10/20/2017 (*67*)	06/03/2018 (*70*)	09/23/2018 (*83*)	06/01/2019 (33)
			10/04/2018 (67)	
Plant/row spacing (cm)	30/50	20/50	20/50	20/50
N and K fertilizer-first application (m/d/y)	08/27/2017	04/16/2018	08/18/2018	04/06/2019
N and K fertilizer-second application (m/d/y)	09/27/2017	05/21/2018	09/18/2018	05/10/2019
Harvest date (m/d/y)	11/10/2017	06/13/2018	10/19/2018	06/12/2019

flow analysis after filtration. In addition, the soil water content of the samples was measured by oven drying at 105 °C for 24 h.

2.4. Installation of lysimeters and collection of leachates

The trial plots were separated by polyvinyl chloride (PVC) plates down to a 90 cm depth to prevent lateral movement of nutrients and water. Eighteen in situ rectangular PVC lysimeters (40 cm length, 50 cm width, 5 cm thick) were installed at a 90 cm soil depth before basal fertilizer was applied. Each lysimeter was filled with sandy gravel, and the top was left open. The same soil volume was removed first without disturbing the surrounding soil, and then the lysimeter was inserted into the soil in conjunction with a leachate collection container whose capacity was 12 L (Zhang et al., 2017; Lee et al., 2013). In brief, nitrates are generally leached downward with irrigation water or rainwater until reaching the lysimeter. The leachates then flow into the collection container where a vacuum pump is present to collect the leachate into a sampling bottle for subsequent quantification.

The irrigation water and rainwater were recorded via a water meter and rain gauge, respectively. The leachate was collected during a 6–7 d period after each irrigation or rainfall event (Yang et al., 2017; Song et al., 2009). After each leaching event, the leachate volume in each lysimeter was measured, and a sample of 100 mL was collected for NO_3^--N determination after filtration via continuous flow analysis.

2.5. Calculations

2.5.1. NUE

The agronomic efficiency (AEN), recovery efficiency (REN), and partial factor productivity (PFPN) of the N applied were selected as NUE indicators, each of which was calculated as follows (Yang et al., 2017; He et al., 2009):

$$\mathrm{AEN} = \frac{\mathrm{Y_a} - \mathrm{Y0_a}}{\mathrm{N_a}} \tag{1}$$

$$\mathrm{REN} = \frac{\mathrm{U_a} - \mathrm{U0_a}}{\mathrm{N_a}} \times 100 \tag{2}$$

$$\mathrm{PFPN} = \frac{\mathrm{Y_a}}{\mathrm{N_a}} \tag{3}$$

where $Y0_a$ and Y_a are the accumulated radish fleshy root yields (kg ha^{-1}) in the N0 plots and N-treated plots, $U0_a$ and U_a are the accumulated plant N uptake (kg ha^{-1}) in the N0 plots and N-treated plots, respectively, and N_a is the accumulated N fertilizer input (kg ha^{-1}).

Another important indicator to evaluate the status of N use is the soil apparent N loss, which was quantified as follows (Zhao et al., 2016):

$$Soil\ apparent\ N\ loss\left(kg\ N\ ha^{-1}\right) = soil\ mineral\ N\ before\ sowing + apparent\ mineralized\ N + fertilizer\ N - soil\ mineral\ N\ at\ harvest - plant\ N\ uptake\ at\ harvest \quad (4)$$

$$Apparent\ mineralized\ N\left(kg\ N\ ha^{-1}\right) = (residual\ soil\ mineral\ N + N\ taken\ up\ by\ the\ plants - soil\ mineral\ N\ before\ sowing)in\ the\ N0\ plots \quad (5)$$

where the soil mineral N content was determined within the 0–100 cm soil profile.

2.5.2. NR in the soil

The calculation of NR within each soil layer was performed as follows:

$$NR\left(kg\ N\ ha^{-1}\right) = CNitrate \times BD \times d \times 0.1 \quad (6)$$

where $C_{Nitrate}$ is the concentration of nitrate in the soil (mg kg^{-1}), BD represents the soil bulk density (g cm^{-3}), d represents the depth of the soil profile (cm), and 0.1 is a conversion coefficient.

$$Fertilizer\ N\ residual\ ratio(\%) = \frac{NR_F - NR_{CK}}{N} \times 100\% \quad (7)$$

where NR_F and NR_{CK} are the NR in the N-treated and N0 plots, respectively, and N is the amount of N applied (kg N ha^{-1}).

2.5.3. Nitrate leaching losses

The seasonal nitrate leaching loss (SNLL) was calculated as follows:

$$SNLL\left(kg\ N\ ha^{-1}season^{-1}\right) = \sum_{i=1}^{n} \frac{C_i \times V_i}{0.5 \times 0.4} \times 0.01 \quad (8)$$

where C_i (mg N L^{-1}) and V_i (L) represent the nitrate concentration and the volume of leached water, respectively, 0.5 and 0.4 (m) represent the width and length of the lysimeter, respectively, and n represents the number of leaching events.

$$Seasonal\ nitrate\ leaching\ factor(SNLF,\%) = \frac{SNLL_F - SNLL_{CK}}{N} \times 100\% \quad (9)$$

where $SNLL_F$ and $SNLL_{CK}$ are seasonal nitrate leaching losses in N-treated and N0 plots (kg N ha^{-1} season^{-1}), respectively, and N is the amount of N fertilizer applied (kg N ha^{-1}).

2.6. Statistical analysis

We tested the significance of differences in radish yield, NUE, NR, nitrate leaching, and other parameters between the different treatments via analysis of variance (ANOVA). The average values were subsequently compared using the least significant difference (LSD) test at $P < 0.05$. The relationships between the amount of N input and radish yield, NUE, NR, and nitrate leaching were quantified via a one-way regression analysis. SAS 9.3 (SAS Institute, Inc., Cary, NC) software was used for all statistical analyses, and all experimental data were analyzed by the use of Excel (2016).

3. Results

3.1. Precipitation, irrigation, and leachate

Total water inputs comprised that from irrigation and precipitation. The inputs of irrigation water were 334, 227, 364, and 317 mm during the four radish growing seasons in the experiment from autumn 2017 to spring 2019, and the seasonal precipitation was 88, 60, 29, and 104 mm, respectively (Fig. 2). The seasonal average leachate amounts for the N0, N60, N120, N180, N240, and N300 treatments across the radish growing periods were 157.0, 160.3, 188.6, 192.7, 173.2, and 196.0 mm, respectively. A total of 18 nitrate leaching events occurred during the radish growing seasons, and apparent differences in the amount of leachate were detected in each event. There were 4, 4, 5, and 5 leaching events in the four seasons, respectively, which resulted in leachate amounts equal to 184, 154, 192, and 180 mm.

3.2. Radish fleshy root yields

The fleshy root yields of radish were significantly affected by N addition (Fig. 3a, $P < 0.05$). The seasonal average fleshy root yields were 26.7, 43.7, 57.9, 63.8, 64.1, and 64.2 t ha^{-1} in the N0, N60, N120, N180, N240, and N300 treatments, respectively. The regression analysis indicated that seasonal average fleshy root yields increased quadratically as the seasonal N input increased (Fig. 3b, $P < 0.001$), with a maximum fleshy root yield of 66.0 t ha^{-1} in response to a N fertilizer rate of 237 kg N ha^{-1}. Nevertheless, no significant yield increase was observed when the N fertilizer rate exceeded 180 kg N ha^{-1}, demonstrating that excessive fertilization can be avoided when aiming for a specific target yield.

3.3. NUE

The NUE was significantly influenced by the seasonal N rate (Fig. 4, $P < 0.05$). The AEN was respectively 282.7, 260.2, 206.1, 155.6, and 124.8 kg kg^{-1} (Fig. 4a); the REN was respectively 66.9, 48.7, 49.5, 38.9, and 31.9% (Fig. 4b); and the PFPN was respectively 727.9, 482.8, 354.5, 266.9, and 213.9 kg kg^{-1} in the N0, N60, N120, N180, N240, and N300 treatments (Fig. 4c). The regression analysis further demonstrated that the AEN, REN, and PFPN decreased linearly with increasing fertilizer N input.

3.4. NR

There were significant differences in nitrate distribution and accumulation within the 0–100 cm soil layer between the different N amounts (Fig. 5). The seasonal average NR in each soil layer significantly enhanced with increasing N fertilizer rate (Fig. 5b, $P < 0.05$). When averaged across experimental seasons, the NR within the 0–100 cm soil layer was 56.0, 71.1, 95.1, 105.5, 144.0, and 170.7 kg N ha^{-1}, respectively, at the N application rates of 0–300 kg N ha^{-1} (Fig. 5a), and increased exponentially with increasing seasonal N input (Fig. 5c, $P < 0.0001$). The fertilizer N residual ratio was 25.2%, 32.6%, 27.5%, 36.7%, and 38.2% at N rates of 60–300 kg N ha^{-1} and increased linearly with increasing N rate (Fig. 5c, $P < 0.05$). These results obviously revealed that relatively high N inputs increase the accumulation of nitrate within the soil profile after crop harvest.

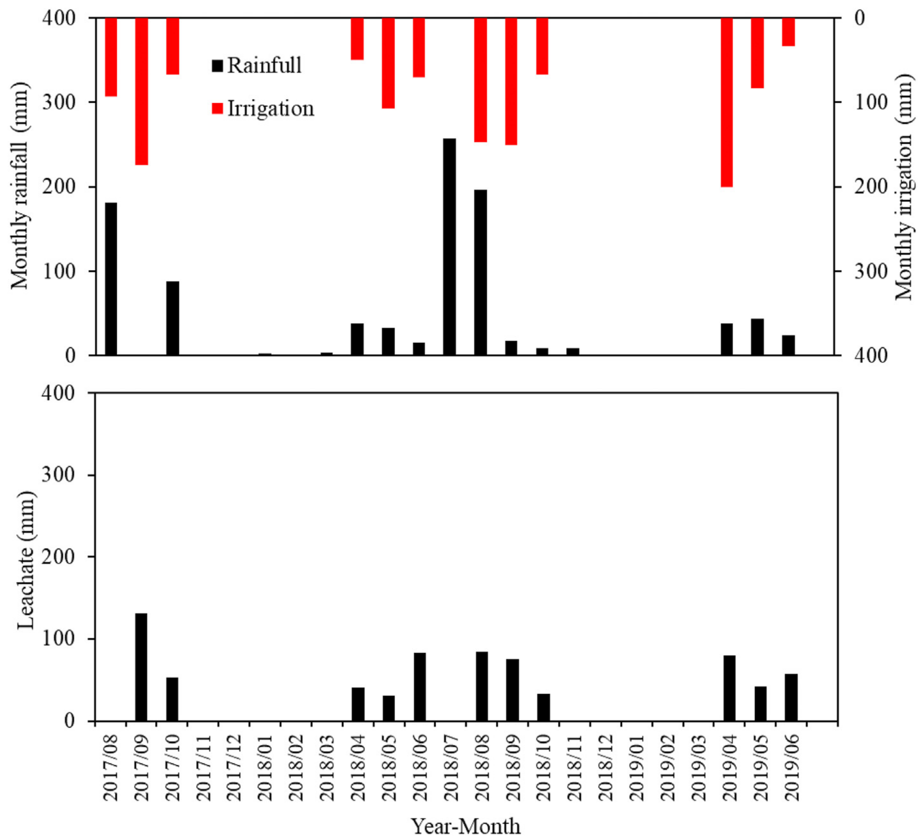

Fig. 2. Distribution of irrigation, rainfall, and leachate amounts during the study period from August 2017 to June 2019 (Note: There are only 10 events of nitrate leaching shown in this figure since 3 nitrate leaching events occurred in September 2017; 2 events in June, August, and September 2018; and 2 events in April and June 2019). The leachate entries represent the average values in the different N fertilizer treatments.

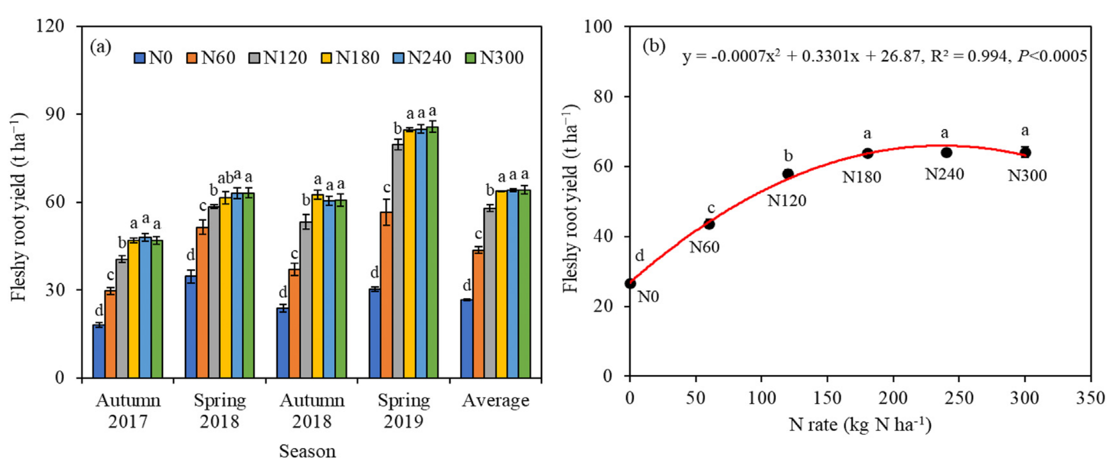

Fig. 3. Fleshy root yields (a) and their relationships with N application rate (b) from autumn 2017 to spring 2019. The vertical bars represent the standard deviations, and the different letters indicate significant differences at $P < 0.05$.

3.5. Nitrate concentration in the leachate and nitrate leaching losses

There were a total of 18 nitrate leaching events during the four-season study (Fig. 6). The nitrate leaching losses and nitrate concentration in the leachate at the 90 cm soil depth were significantly impacted by the seasonal N fertilizer rate (Fig. 6, $P < 0.05$). Averaged among events, the nitrate concentrations in the leachates were 5.1, 7.5, 11.1, 19.1, 28.7, and 35.6 mg N L^{-1} for the N0, N60, N120, N180, N240, and N300 treatments, respectively (Fig. 6a and b), and the corresponding nitrate leaching losses were 1.8, 2.6, 4.9, 8.2, 10.8, and 15.6 kg N ha^{-1} (Fig. 6c and d), respectively. Nitrate concentrations and nitrate leaching losses in the leachate obviously varied greatly between the different leaching events (Fig. 6a and c). Nevertheless, on the whole, both of these factors generally increased as the N fertilizer rate increased.

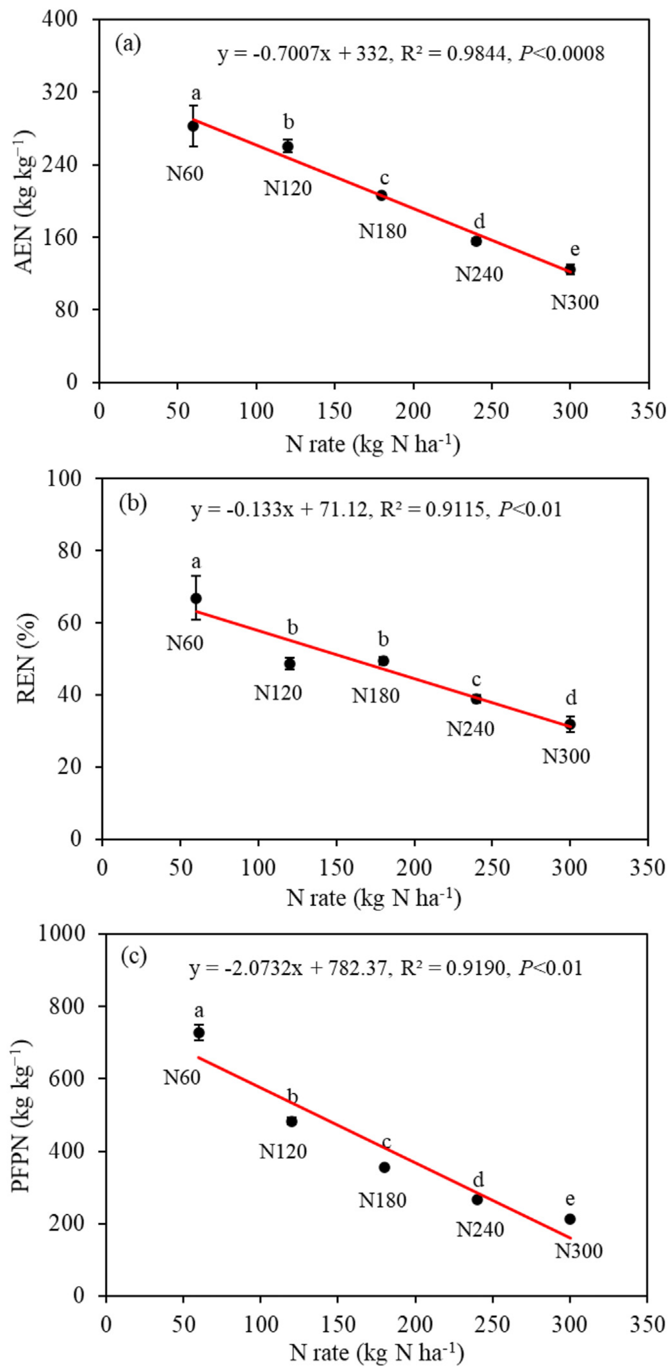

Fig. 4. Regressions between N application rate and accumulated agronomic efficiency (AEN, a), recovery efficiency (REN, b), and partial factor productivity (PFPN, c) of applied N from autumn 2017 to spring 2019. The vertical bars represent the standard deviations, and the different letters indicate significant differences at $P < 0.05$.

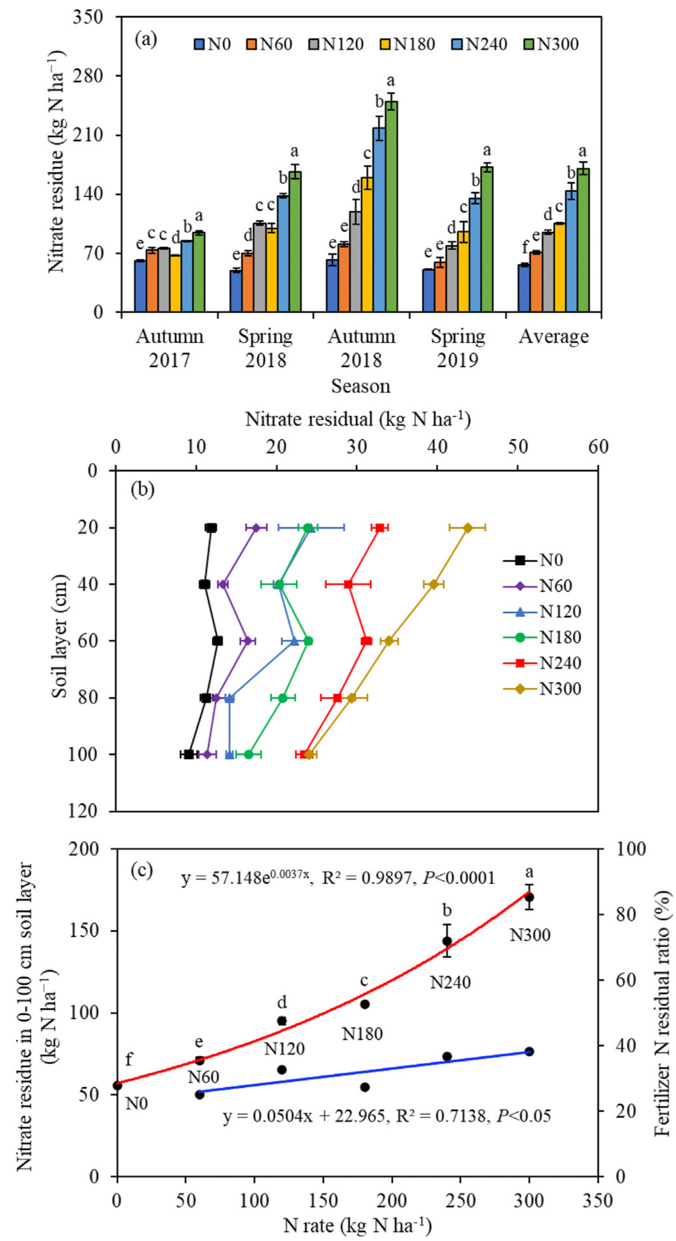

Fig. 5. Nitrate residue (a) and nitrate distribution (b) within the 0–100 cm deep soil layer, fertilizer N residual ratio (c), and their regressions with the seasonal N application rate (c) from autumn 2017 to spring 2019. The vertical and horizontal bars represent the standard deviations, and the different letters indicate significant differences at $P < 0.05$.

3.6. SNLL

The SNLL and SNLF differed significantly between the different N fertilizer rates (Fig. 7a and c, $P < 0.05$). The SNLL averaged 8.2, 11.5, 21.4, 36.4, 49.3, and 71.5 kg N ha^{-1} in the N0, N60, N120, N180, N240, and N300 treatments, respectively, and the SNLF averaged 6.0, 11.3, 15.8, 17.3, and 21.2%, respectively. The SNLL and SNLF increased exponentially and linearly, respectively, as the N amount increased (Fig. 7b and d, $P < 0.0001$), suggesting that excessive N fertilizer inputs increase the loss proportion of N fertilizer.

4. Discussion

4.1. Fertilization, radish yield, and NUE

Crop yield can be significantly improved through N fertilization (Zhang et al., 2017; Min et al., 2012). In our four-season field experiment, N fertilizer application increased the radish fleshy root yield by 63.5–140.2%. However, crop yields generally do not increase markedly when the N fertilizer inputs exceed some threshold (Yang et al., 2017; Tilman et al., 2002). Under most field conditions, the relationship between N input and yield has been best described by linear-plus-plateau or quadratic regression models (Qiu et al., 2015; Zhao et al., 2010), which is primarily due to the negative consequences caused by excessive fertilization (e.g.,

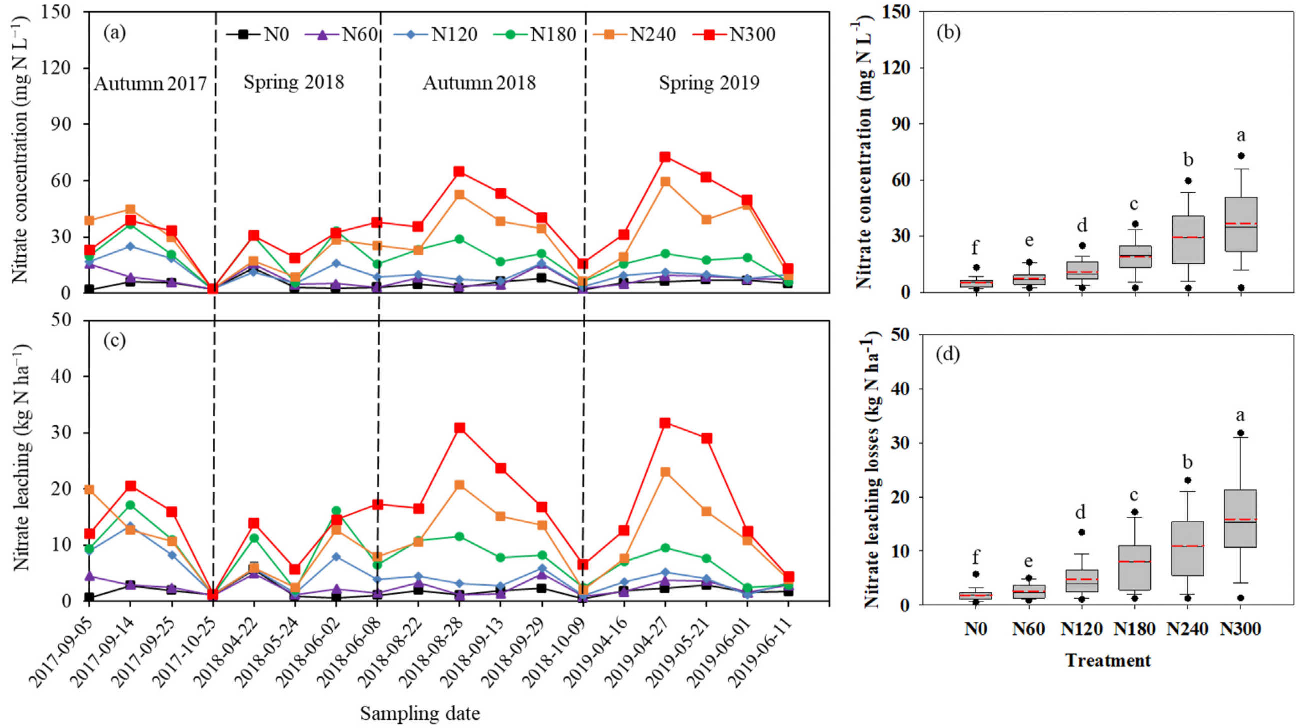

Fig. 6. Nitrate concentrations in the leachate (a, b) and nitrate leaching losses (c, d) in the 18 leaching events from September 2017 to June 2019. Box-whisker diagrams (b, d) showing the average, 25th, 50th, and 75th percentiles.

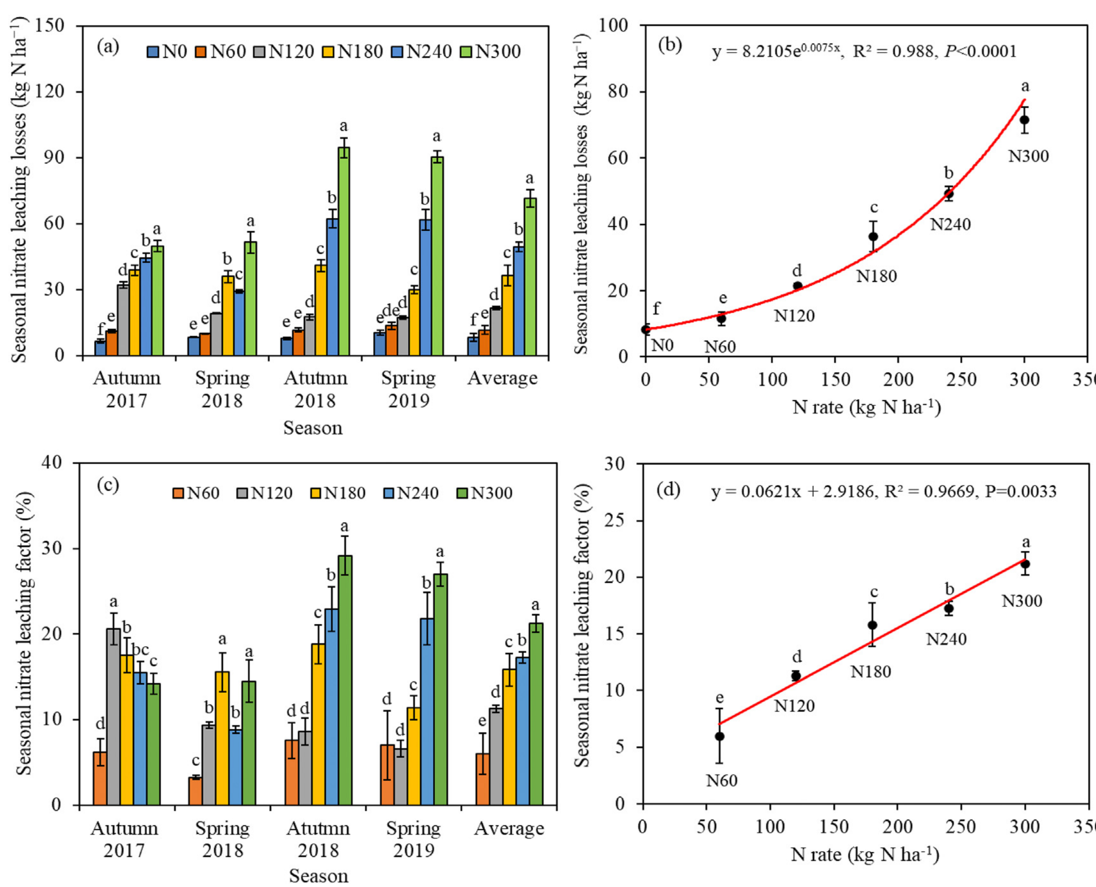

Fig. 7. Seasonal nitrate leaching losses (a), seasonal nitrate leaching factor (c) and their regressions with the seasonal N application rate (b, d) from autumn 2017 to spring 2019. The vertical bars are the standard deviations, and the different letters indicate significant differences at $P < 0.05$.

increasing vegetative growth at the cost of root yield, soil acidification and hardening) as well as the limitations of water, nutrients, and solar radiation availability (Liu et al., 2016; Zhao et al., 2010). The results of this study showed that the radish yields did not increase significantly when the N usage exceeded 180 kg N ha^{-1} and that N rates of 240 and 300 kg N ha^{-1} exceeded the amount of N needed for maximum yield (i.e., 237 kg N ha^{-1}). These results suggest that excessive fertilization did not significantly improve radish yields and that an approximate 40% reduction in N fertilizer inputs (to 120 kg N ha^{-1}) by local farmers (i.e., 300 kg N ha^{-1}) in a single season did not result in any yield losses. While a portion of the excess N fertilizer accumulates within the soil profile, a portion can be lost to the environment via leaching and volatilization of ammonia and other gases such as NO and N_2O (Cameron et al., 2013). NUE always decreases as N input increases (Gu et al., 2017), in accordance with the linear reductions in this study for AE, RE, and PFP with increasing N fertilizer input (Fig. 4). These results indicated that the applied N was used more efficiently under a moderate N fertilizer amount than under the conventional N fertilizer amount. The REN of approximately 40% for vegetable crops would be considered inefficient, which causes concerns in most parts of the world (Zhu et al., 2005). Thus, an REN of approximately 30% resulting from the current farmers' practice (i.e., N300 treatment) for radish cropping systems in northern China is extremely inefficient, mainly because of the excessive N fertilizer applied in vegetable production (Huang et al., 2017).

4.2. Nitrate residue and leaching

Excessive applications of N fertilizer lead to the accumulation of large amounts of nitrate within the soil profile (Ju et al., 2009). In our study, the NR measured within the 0–100 cm deep soil layer averaged 71.1–170.7 kg N ha^{-1} and increased exponentially when the seasonal N fertilizer rate increased from 60 to 300 kg N ha^{-1}. Our findings are similar to those of research on grain crop (i.e., winter wheat), in which a 9-year fixed site field test carried out in northern China revealed that the amount of NR ranged from 54.5 to 222.0 kg N ha^{-1} within the 0–100 cm deep soil layer in response to N rates of 80–320 kg N ha^{-1} and that the NR was also exponentially related to N fertilizer rate (Dai et al., 2015). In the present study, a 40% reduction in the seasonal N fertilizer rate compared with the conventional N rate (i.e., 300 kg N ha^{-1}) significantly reduced the NR by 28.5%–44.6%, with an average of 38.2%. The average fertilizer N residual ratio ranged from 25.2% to 38.2% in response to N rates of 60–300 kg N ha^{-1}, demonstrating that approximately 25.2%–38.2% of the applied fertilizer N was accumulated in the soil as nitrates; this range was similar to the values of 18.0%–38.0% range previously reported in an intensive maize/wheat rotation system in south-central China (Yang et al., 2017). The mounting link connecting NR and seasonal N fertilizer rate (Fig. 5c) confirmed that increasing the N fertilizer rate increased the residual percentage of N fertilizer in the soil, which was demonstrated by a linear regression between the fertilizer N residual ratio and the N fertilizer rate (Fig. 5c). These accumulated nitrates are not entirely used by the next season's crop, particularly when they exceed the amount needed by the crop, but gradually percolate to a deeper soil layer after a number of seasons or years with large amounts of irrigation or heavy rainfall (Yang et al., 2015; Ju et al., 2009).

The average SNLL (11.5–71.5 kg N ha^{-1}) in response to N rates ranging from 60 to 300 kg N ha^{-1} in this study was much greater than that for a grain crop (i.e., winter wheat), for which the nitrate leaching loss averaged 10.1–15.8 kg N ha^{-1} (Yang et al., 2015). However, this loss was much lower than that reported in a subtropical vegetable cropping system (Zhang et al., 2017). These differences can be attributed mainly to differences in water and N inputs (Gholamhoseini et al., 2013; Li et al., 2007), as well as the shallow roots of vegetables and the permeability of soil (Thorup, 2006). The average SNLF ranged from 6.0% to 21.2% in response to N rates of 60–300 kg N ha^{-1}, indicating that approximately 6.0%–21.2% of the applied N fertilizer was lost via nitrate leaching in our study. These results are essentially consistent with the range 3.8%–18.9% previously reported in an intensive vegetable production system in northern China (Zhu et al., 2005). In addition, these results showed that nitrate leaching losses accounted for 21.2% of the applied N under the high conventional N rate used by local farmers (i.e., 300 kg N ha^{-1}) in field vegetable systems in northern China, which was in agreement with the losses reported by Min et al. (2012) (i.e., 19.7%) and Zhao et al. (2010) (i.e., 21.7%) in intensive vegetable production systems in China. It was also reported that nitrate leaching is one of the crucial routes of N loss under high N fertilizer inputs in intensively managed vegetable cropping systems (Min et al., 2011). The exponential relationship between SNLL and the amount of N applied revealed an increasing ratio of SNLL to the seasonal N fertilizer rate, which was demonstrated by a linear relationship between SNLF and N fertilizer rate (Fig. 7); these results are in accordance with those of recent study by Yang et al. (2017) in grain cropping systems in northern China. Taken together, these results indicated that excessive N fertilizer input increases the proportion of N losses due to leaching. Therefore, it is imperative to reduce N loss due to leaching in field vegetable cropping systems.

4.3. Identifying critical N fertilizer rates for optimum yields and minimum nitrate leaching losses

The goal of sustainable agriculture is to meet the increasing food demands of the increasing human population with high crop productivity and nutrient efficiency while minimizing the negative influences on the environment (Norse and Ju, 2015; Ju et al., 2009). Many studies have shown that applying appropriate amounts of fertilizer is the most effective strategy for reducing agricultural impacts on the environment caused by nitrate leaching (Min et al., 2012; Zhang et al., 2015b). We identified a critical N fertilizer rate that results in a balance between radish yield, NR in the soil, and nitrate leaching losses (Fig. 8). In the current study, the amount of nitrate leached into the groundwater was affected by the amounts of irrigation and precipitation, and the average seasonal cumulative drainage from the field was 178 mm during the study period. If the standard of drinking water of 11.3 mg NO_3^--N L^{-1} specified by the

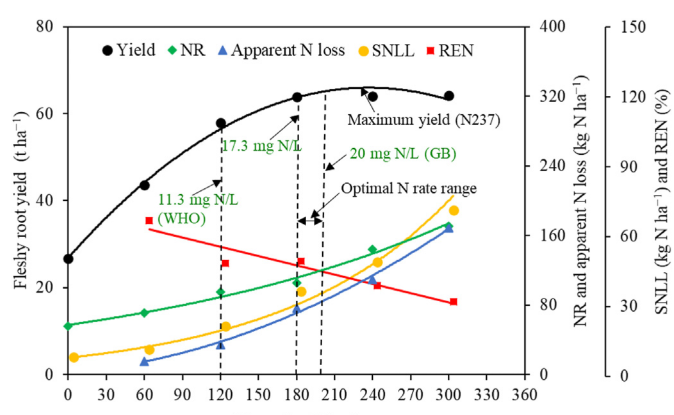

Fig. 8. Fleshy root yield, nitrate residue (NR) within the 0–100 cm deep soil layer, apparent N loss, seasonal nitrate leaching losses (SNLL), and recovery efficiency of N (REN) as regression functions with the seasonal N application rate from 2017 to 2019.

WHO is used as a standard, the amount of nitrate leached into the groundwater during the radish growing season should not exceed 20.1 kg N ha^{-1}, and the corresponding N fertilizer rate should not exceed 120 kg N ha^{-1}. However, the radish yield (i.e., 56.4 t ha^{-1}) under this N fertilizer rate significantly decreased, which goes against the reality of the demands for high production in China, because the standard was established from the perspective of environmental protection without accounting for the goal of high yields. Therefore, this standard is still insufficient for guaranteeing sustainable production in China, and further optimization of N fertilizer practices, such as the choice of fertilizer source (fast or slow release) and the method and timing of N applications, is needed. Additional measures, such as well-managed irrigation techniques (e.g., fertigation) and intercropping, can also help prevent high N losses due to leaching (Agostini et al., 2010). In China, considering the differences in groundwater and surface water from those in other countries (such as the United States and European Union countries) and the status of groundwater utilization, the maximum NO_3^--N concentration in the groundwater can reach 20 mg N L^{-1} according to the Standard for Groundwater Quality GB/T14848-2017 in China (Zhang et al., 2018). Thus, the amount of nitrate leached into groundwater should not exceed 35.8 kg N ha^{-1}, which was greater than the amount of nitrate leached into groundwater for the grain crop (i.e., maize) in northern China, and the amount of nitrate leaching was also determined according to the national standard (i.e., NO_3^--N $\leq$ 20 mg N L^{-1}) (Ju and Zhang, 2017). The corresponding N rate of 196 kg N ha^{-1} was much less than the N rate used by farmers and did not reduce radish yields significantly. Additionally, the N fertilizer rate of 180 kg N ha^{-1} in this study did not significantly reduce the radish yield and resulted in 31.7 kg N ha^{-1} of nitrate leached into the groundwater according to the response curve of SNLL and the nitrate concentration in the leachate was 17.0 mg N L^{-1}. Therefore, the critical N fertilizer rate ranged from 180 to 196 kg N ha^{-1} for optimum crop yields and minimum nitrate leaching losses.

A reasonable amount of NR within the root zone is a key factor for increased crop yields (Fan et al., 2010). Research on grain crops has shown that, for high production, the NR within the 0–90 cm deep soil layer should not exceed 150 kg N ha^{-1} after harvesting in northern China (Cui et al., 2008; Zhong et al., 2006). In the present study, the NR response curve demonstrated that the N application range of 180–196 kg N ha^{-1} corresponded to a NR amount ranging from 111.2 to 118.0 kg N ha^{-1} within the 0–100 cm deep soil layer (Fig. 8), which is far below the NR in intensively cultivated vegetable cropping systems in northern China (Zhu et al., 2005) and far below that in subtropical vegetable production systems (Zhang et al., 2017). Therefore, the NR within the 0–100 cm deep soil layer in radish fields should not exceed 118.0 kg N ha^{-1} after harvest. The NR in response to the N fertilizer rate ranging from 180 to 196 kg N ha^{-1} may be conducive to obtaining sustainable crop yields and minimizing environmental costs because the amount of N applied within this range, which results in a high REN (44.3–47.2%) and low SNLL (31.7–35.8 kg N ha^{-1}) and soil apparent N loss (59.4–69.5 kg N ha^{-1}), was sufficient to achieve high vegetable production throughout this four-season study. In addition, compared to the conventional N fertilizer amount applied by farmers (i.e., 300 kg N ha^{-1}), the SNLL, NR in the soil, and apparent N loss could be reduced by 35.7–39.8 kg N ha^{-1} (49.9%–55.7%), 52.7–59.5 kg N ha^{-1} (30.9%–35.0%), and 99.6–109.7 kg N ha^{-1} (58.9%–64.9%) under this N application range, respectively. Thus, on the basis of the dual goals of environmental protection and high agricultural yield, we recommend a critical N application range of 180–196 kg N ha^{-1} $season^{-1}$ for field radish crops.

5. Conclusion

Taken together, the results of this study showed that N fertilizer rates ranging from 180 to 196 kg N ha^{-1} provided optimum crop yields with acceptable nitrate leaching losses, and compared with the conventional N fertilization amount, this amount resulted in a greater NUE, lower N losses due to nitrate residue and leaching, and lower apparent N loss. Thus, the critical N fertilizer rate ranging from 180 to 196 kg N ha^{-1} is recommended for radish fields in northern China. This study provides theoretical guidance for local farmers with the goal of better fertilization and environmental protection practices. Future studies are urgently needed to investigate the use of slow-release fertilizers or enhanced-efficiency fertilizers combined with water-saving techniques (e.g., fertigation) in field vegetable cropping systems in northern China to further reduce N losses in the form of leaching while sustaining high yields.

Authorship contribution statement

Jiajia Zhang: Conceptualization, Methodology, Formal analysis, Writing - original draft. **Ping He:** Writing - review & editing, Funding acquisition. **Wencheng Ding:** Writing - review & editing. **Sami Ullah:** Writing - review & editing. **Tanveer Abbas:** Writing - review & editing. **Mingyue Li:** Performed the experiments. **Chao Ai:** Supervision. **Wei Zhou:** Resources, Supervision.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

The values in italics represent the amount of water applied (mm).

Acknowledgments

We appreciate the financial support from the National Key Research & Development Program of China (No. 2016YFD0200103 and 2016YFD0200109) and the Fundamental Research Funds for Central Nonprofit Scientific Institution (No. 1610132019047).

References

Agostini, F., Tei, F., Silgram, M., Farneselli, M., Benincasa, P., Aller, M.F., 2010. Decreasing Nitrate Leaching in Vegetable Crops with Better N Management. In: Lichtfouse, E. (Ed.), Genetic Engineering, Biofertilisation, Soil Quality and Organic Farming. Springer, Dordrecht, the Netherlands, pp. 147–200.

Cameron, K.C., Di, H.J., Moir, J.L., 2013. Nitrogen losses from the soil-plant system: a review. Ann. Appl. Biol. 162, 145–173.

Cui, Z.L., Zhang, F.S., Miao, Y.X., Sun, Q.P., Li, F., Chen, X.P., Li, J.L., Ye, Y.L., Yang, Z.P., Zhang, Q., Liu, C.S., 2008. Soil nitrate-N levels required for high yield maize production in the North China Plain. Nutrient Cycl. Agroecosyst. 82, 187–196.

Chen, Q., Zhang, X.S., Zhang, H.Y., Christie, P., Li, X.L., Horlacher, D., Liebig, H.P., 2004. Evaluation of current fertilizer practice and soil fertility in vegetable production in the Beijing region. Nutrient Cycl. Agroecosyst. 69, 51–58.

Dai, J., Wang, Z.H., Li, F.C., He, G., Wang, S., Li, Q., Cao, H.B., Luo, L.C., Zan, Y.L., Meng, X.Y., Zhang, W.W., Wang, R.H., Malhi, S., 2015. Optimizing nitrogen input by balancing winter wheat yield and residual nitrate-N in soil in a long-term dryland field experiment in the Loess Plateau of China. Field Crop. Res. 181, 32–41.

Dong, Q., Dang, T.H., Guo, L.S., Hao, M.D., 2019. Effect of different mulching measures on nitrate nitrogen leaching in spring maize planting system in south of Loess Plateau. Agric. Water Manag. 213, 654–658.

Eichler, F., Schulz, D., 1998. The nitrogen reduction program in the Federal Republic of Germany. Environ. Pollut 102, 609–617.

European Commission, 1999. Agriculture, environment, rural development: facts and figures—a challenge for agriculture. Office for official publications of the European communities, Luxembourg.

FAO., 2017. Faostat. Fao. http://faostat.fao.org. (Accessed 6 July 2018).

Fan, J., Hao, M.D., Malhi, S.S., 2010. Accumulation of nitrate N in the soil profile and

its implications for the environment under dryland agriculture in northern China: a review. Can. J. Soil Sci. 90, 423–429.
Gholamhoseini, M., AghaAlikhani, M., Modarres Sanavy, S.A.M., Mirlatifi, S.M., 2013. Interactions of irrigation, weed and nitrogen on corn yield: nitrogen use efficiency and nitrate leaching. Agric. Water Manag. 126, 9–18.
Gu, B.J., Ju, X.T., Chang, S.X., Ge, Y., Chang, J., 2017. Nitrogen use efficiencies in Chinese agricultural systems and implications for food security and environmental protection. Reg. Environ. Change 17, 1217–1227.
He, P., Li, S.T., Jin, J.Y., Wang, H.T., Li, C.J., Wang, Y.L., Cui, R.Z., 2009. Performance of an optimized nutrient management in north-central China. Agron. J. 101, 1489–1496.
Huang, S.W., Tang, J.W., Li, C.H., Zhang, H.Z., Yuan, S., 2017. Reducing potential of chemical fertilizers and scientific fertilization countermeasure in vegetable production in China. Plant Nutr. Fert. Sci. 23, 1480–1493 (in Chinese with English abstract).
Ju, X.T., Zhang, C., 2017. Nitrogen cycling and environmental impacts in upland agricultural soils in North China: a review. J Integr Agr 16, 2848–2862.
Ju, X.T., Xing, G.X., Chen, X.P., Zhang, S.L., Zhang, L.J., Liu, X.J., Cui, Z.L., Yin, B., Peter, Christie, Zhu, Z.L., Zhang, F.S., 2009. Reducing environmental risk by improving N management in intensive Chinese agricultural systems. PNAS. org_cgi_doi_10.1073_pnas.0813417106. www.pnas.
Ju, X.T., Kou, C.L., Zhang, F.S., Christie, P., 2006. Nitrogen balance and groundwater nitrate contamination: comparison among three intensive cropping systems on the North China Plain. Environ. Pollut 143, 117–125.
Ju, X.T., Liu, X.J., Zhang, F.S., Roelcke, M., 2004. Nitrogen fertilization, soil nitrate accumulation, and policy recommendations in several agricultural regions of China. AMBIO: J. Hum. Environ. 33, 300–305.
Kaushal, S.S., Groffman, P.M., Band, L.E., Elliott, E.M., Shields, C.A., Kendall, C., 2011. Tracking nonpoint source nitrogen pollution in human-impacted watersheds. Environ. Sci. Technol. 45, 8225–8232.
Lee, C., Feyereisen, G.W., Hristov, A.N., Dell, C.J., Kaye, J., Beegle, D., 2013. Effects of dietary protein concentration on ammonia volatilization, nitrate leaching, and plant nitrogen uptake from dairy manure applied to lysimeters. J. Environ. Qual. 43, 398–408.
Li, X.X., Hu, C.S., Delgado, J.A., Zhang, Y.M., Ouyang, Z.Y., 2007. Increased nitrogen use efficiencies as a key mitigation alternative to reduce nitrate leaching in North China Plain. Agric. Water Manag. 89, 137–147.
Liu, H., Wang, Z.H., Yu, R., Li, F.C., Li, K.Y., Cao, H.B., Yang, N., Li, M.H., Dai, J., Zan, Y.L., Li, Q., Xue, C., He, G., Huang, D.L., Huang, M., Liu, J.S., Qiu, W.H., Zhao, H.B., Mao, H., 2016. Optimal nitrogen input for higher efficiency and lower environmental impacts of winter wheat production in China. Agric. Ecosyst. Environ. 224, 1–11.
Min, J., Zhang, H.L., Shi, W.M., 2012. Optimizing nitrogen input to reduce nitrate leaching loss in greenhouse vegetable production. Agric. Water Manag. 111, 53–59.
Min, J., Zhao, X., Shi, W.M., Xing, G.X., Zhu, Z.L., 2011. Nitrogen balance and loss in a greenhouse vegetable system in Southeastern China. Pedosphere 21, 464–472.
Norse, D., Ju, X.T., 2015. Environmental costs of China's food security. Agric. Ecosyst. Environ. 209, 5–14.
Padilla, F.M., Marisa, G., Francisco, M.A., 2018. Global trends in nitrate leaching research in the 1960–2017 period. Sci. Total Environ. 643, 400–413.
Qafoku, N., 2014. Overview of different aspects of climate change effects on Soil-sPacific Northwest national laboratory, Richland, WA (US). Available. http://www.osti.gov/scitech/biblio/1167316.
Qiu, S.J., He, P., Zhao, S.C., Li, W.J., Xie, J.G., Hou, Y.P., Grant, C.A., Zhou, W., Jin, J.Y., 2015. Impact of nitrogen rate on maize yield and nitrogen use efficiencies in northeast China. Agron. J. 107, 305–313.
Sahu, P.K., 2004. Statistical analysis of vegetable production in India, China, and the world. J. Veg. Crop Prod. 10, 3–9.
Song, X.Z., Zhao, C.X., Wang, X.L., Li, J., 2009. Study of nitrate leaching and nitrogen fate under intensive vegetable production pattern in northern China. CR Biol. 332, 385–392.
Shi, W.M., Yao, J., Yan, F., 2009. Vegetable cultivation under greenhouse conditions leads to rapid accumulation of nutrients, acidification and salinity of soils and groundwater contamination in South-Eastern China. Nutrient Cycl. Agroecosyst. 83, 73–84.
Thorup, K.K., 2006. Effect of deep and shallow root systems on the dynamics of soil inorganic N during 3-year crop rotations. Plant Soil 288, 233–248.
Tilman, D., Cassman, K.G., Matson, P.A., Naylor, R., Polasky, S., 2002. Agricultural sustainability and intensive production practices. Nature 418, 671–677.
Yang, X.L., Lu, Y.L., Ding, Y., Yin, X.F., Raza, S., Tong, Y.A., 2017. Optimising nitrogen fertilisation: a key to improving nitrogen-use efficiency and minimising nitrate leaching losses in an intensive wheat/maize rotation (2008–2014). Field Crop. Res. 206, 1–10.
Yang, X.L., Lu, Y.L., Tong, Y.A., Yin, X.F., 2015. A 5-year lysimeter monitoring of nitrate leaching from wheat–maize rotation system: comparison between optimum N fertilization and conventional farmer N fertilization. Agric. Ecosyst. Environ. Times 199, 34–42.
Zhang, J.J., He, P., Ding, W.C., Ullah, S., Abbas, T., Xu, X.P., Ai, C., Li, M.Y., Cui, R.Z., Zhou, W., 2019a. Estimating nutrient uptake requirements for radish cultivated in China based on QUEFTS model. Sci. Rep. 9, 11663.
Zhang, J.J., He, P., Ding, W.C., Xu, X.P., Ullah, S., Abbas, T., Ai, C., Li, M.Y., Cui, R.Z., Zhou, W., 2019b. Establishment and validation of Nutrient Expert system for radish fertilization management in China. Agron. J. 111, 2435–2444.
Zhang, Y.T., Wang, H.Y., Lei, Q.L., Zhang, J.Z., Zhai, L.M., Ren, T.Z., Liu, H.B., 2018. Recommended methods for optimal nitrogen application rate. Sci. Agric. Sin. 51, 2937–2947.
Zhang, B.G., Li, Q., Cao, J., Zhang, C.Y., Song, Z., Zhang, F.S., Chen, X.P., 2017. Reducing nitrogen leaching in a subtropical vegetable system. Agric. Ecosyst. Environ. 241, 133–141.
Zhang, X., Davidson, E.A., Mauzerall, D.L., Searchinger, T.D., Dumas, P., Shen, Y., 2015a. Managing nitrogen for sustainable development. Nature 528, 51–59.
Zhang, Y.T., Wang, H.Y., Liu, S., Lei, Q.L., Liu, Jian, He, J.Q., Zhai, L.M., Ren, T.Z., Liu, H.B., 2015b. Identifying critical nitrogen application rate for maize yield and nitrate leaching in a Haplic Luvisol soil using the DNDC model. Sci. Total Environ. 514, 388–398.
Zhang, X.S., 2005. Integrated nitrogen management system for intensive vegetable production in Beijing suburb. Resources and Environment Faculty. Ph.D. dissertation. China Agricultural University, Beijing.
Zhao, R.R., He, P., Xie, J.G., Johnston, A.M., Xu, X.P., Qiu, S.J., Zhao, S.C., 2016. Ecological intensification management of maize in northeast China: agronomic and environmental response. Agric. Ecosyst. Environ. 224, 123–130.
Zhao, C.S., Hu, C.X., Huang, W., Sun, X.C., Tan, Q.L., Di, H.J., 2010. A lysimeter study of nitrate leaching and optimum nitrogen application rates for intensively irrigated vegetable production systems in Central China. J. Soils Sed. 10, 9–17.
Zhao, T.K., Zhang, C.J., Du, L.F., Liu, B.C., An, Z.Z., Sun, Y.X., 2007. Investigation on nitrate concentration in groundwater in seven provinces (city) surrounding the Bo-Hai Sea. J. Agro-Environ. Sci. 26, 779–783 (in Chinese with English abstract).
Zhong, Qian, Ju, X.T., Zhang, F.S., 2006. Analysis of environmental endurance of winter wheat/Summer maize rotation system to nitrogen in North China Plain. Plant Nutr. Fert. Sci. 12, 285–293.
Zhu, J.H., Li, X.L., Christie, P., Li, J.L., 2005. Environmental implications of low nitrogen use efficiency in excessively fertilized hot pepper (*Capsicum frutescens* L.) cropping systems. Agric. Ecosyst. Environ. 111, 70–80.