Nitrogen source and fate of typical orchard with gentle slope in semi-arid areas

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Abstract: Excessive nitrogen (N) exports caused by human activities are one of the main reasons for the numerous environmental problems in agricultural production. Orchards, as an essential part of agricultural production, play a crucial role in rural economic development and ecological environment construction. Understanding the migration pathways of N in orchards is significant for the scientific management of orchards and the reduction of environmental pollution. In this research, the source and fate of N in a typical orchard in Beijing were quantitatively analyzed. N management strategies were proposed in combination with agricultural production habits. The total N input into the orchard was 487.19 kg/hm^2·a, of which 85.44%, 10.99%, 3.30% and 0.27% of N input were from fertilizer application, atmospheric deposition, biological N fixation and pesticide, respectively. A large amount of N fertilizer application was the primary source of N input in the orchard. For the N fate, the N surplus in the soil could reach up to 68.40% of total N inputs, and only 20.16% were absorbed and utilized by plants. The amount of N losses through ammonia volatilization, runoff and sediment, nitrification and denitrification accounted for 10.68%, 0.39% and 0.37%, respectively. N input in the orchard mainly remained in soil, while N loss was mainly through ammonia volatilization. There were 176.72, 99.00, and 57.52 kg/hm^2·a N surplus in 0-40 cm, 40-80 cm, and over 80 cm soil layers, respectively. To deal with the N accumulation on the soil surface and the migration of N from the soil surface to the deep layer of orchards, reducing N fertilizer application, substituting circular furrow for the whole orchard fertilization, adjusting irrigation schedule by reducing the amount of single irrigation, increasing the frequency of irrigation to three times in the normal year, and adopting efficient water-saving irrigation technology are realizable methods.

Keywords: gentle slope orchard, N accumulation-migration, N fate, N source, semi-arid area
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1 Introduction

Nitrogen (N) is a crucial constituent of various organic compounds and serves as a vital nutrient element for plant growth and reproduction[1,2]. In their quest for high quality and high yield of crops, farmers frequently resort to indiscriminate application of large amounts of N fertilizer. This practice leads to a host of environmental issues, including non-point source pollution and water eutrophication[3,4].

Numerous studies have demonstrated that human activities have significantly impacted regional N input and output, leading to a disruption of global terrestrial ecosystems N balance[5]. Research on N balance, N budget, N input-output and net anthropologic N inputs (NANI) has become a hot issue, focusing on macro scale with long-term series[6,7]. To quantify NANI at global, regional, and national scales, researchers have analyzed human-induced changes in N cycling processes[2,8]. A biochemical and process-based model, manure-DNDC, has been used to determine N discharge fluxes from crop fields and livestock farms[9]. These studies calculated on NANI, N balance, N budget and N input-output have focused on estimating the equilibrium state between N-input and N-output in study area[10]. Although they discuss N input and output in macroscopical regions through different pathways, there is no in-depth quantitative research on the source and fate of the entire N life cycle. Macroscopical regions often contains many different farmland ecosystems, which have different ways of N uptake and utilization. Therefore, there are some limitations when using these results to guide N management in different farmland ecosystems. It is significant to explore the source and fate of all N input in farmland ecosystem based on the principle of N conservation.

To accurately understand the N status of different farmland ecosystems, numerous studies have been conducted to investigate

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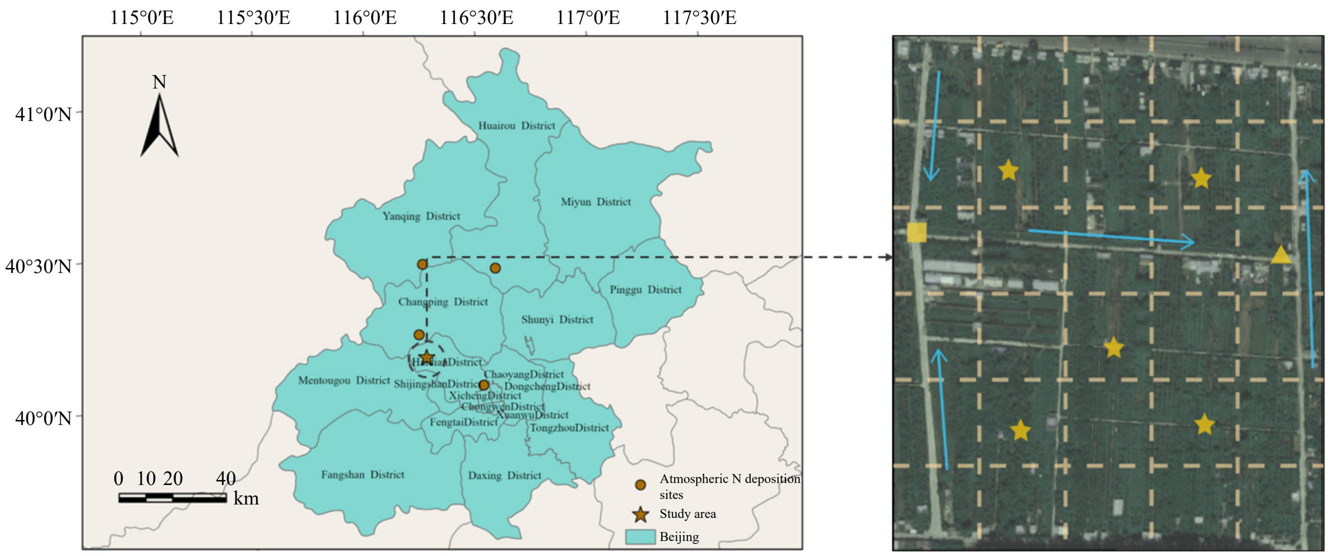
the N balance and influencing factors of various farmland crops at micro scale[11]. Long-term experimental sites have been established to monitor and mathematically analyze in-situ soil N balances associated with various green manures and rice rotations[12]. N surplus values in the top 90 cm and 90-180 cm of soil have been extensively assessed using N balance theory in major intensive cropping systems[13]. Studies have also investigated the effect of ruzigrass, palisade grass and guinea grass on N input, output and partial balance in a cropping system where maize was grown after these species[14]. These studies have primarily focused on N balance in soils of cropping ecosystems and grass ecosystems, which typically have shallow root system, short growth period and two or three crops a year. However, fruit trees in orchards have unique characteristics, including tall trees, long growth cycles, deep roots, low planting density and fruiting once a year[15,16]. Thus, the N absorption, utilization, migration cycle, and balance in orchard ecosystems may differ from those in farmland ecosystems. Current research on N in orchard ecosystems mainly focuses on the relationship between soil N fertilizer application and product yield, the seasonal dynamic characteristics of soil N and the impact of ground management measures on soil N loss[17,18]. However, systematic studies on all source and fate of N and the dynamic migration characteristics of N in orchard ecosystem are scarce. Therefore, it is urgent to combine the research methods of N input and output in orchard at macro scale and the research methods of N balance in soil at micro scale to explore whole source and fate of N in orchard.

This study aimed to: 1) quantify N source in orchards, including fertilizer, pesticide, atmospheric deposition and biological fixed N; 2) in-depth analyze the pathways of N migration based on the N cycle characteristics to support environmental risk assessment; 3) propose N management strategies based on the quantitative analysis of N cycle and agricultural practices in orchards.

2 Materials and methods

2.1 Study area

This study was conducted in 2019 in Niegezhuang village, Sujiatuo Town, Haidian District, Beijing, China. The experimental site, as illustrated in Figure 1, is situated at 116°07'25"E, 40°05'51"N, covers an area of 17.1 hm^2 and has an average altitude of 57 m. The area falls under a warm temperate semi humid and semi-arid monsoon climate, with an average temperature of 13.33°C and an average precipitation of 493.12 mm from 1999 to 2018. The soil in the orchard is classified as cinnamon soil, and its physical and chemical properties are listed in Table 1.



a. Geographical location of the study area b. Location of data monitoring points

Note: The blue arrow indicates the flow direction of runoff, the yellow square indicates the runoff inlet, the triangle indicates the runoff outlet, and the five-pointed star indicates the ammonia volatilization test site.

Figure 1 Overview of the study area

Table 1 Physical and chemical properties of soil in study site

Soil type	Soil texture/%			Soil depth/cm	Soil density/ (g·cm^{-3})	Initial soil water content/%	Field capacity/%	Organic matter/ (g·kg^{-1})	Total N/ (g·kg^{-1})	Total phosphorus/ (g·kg^{-1})
	Clay (<0.002 mm)	Silt (0.002-0.02 mm)	Sand (0.02-2.0 mm)							
Sandy loam	18.12	22.68	59.20	0-40	1.46	17.19	23.57	14.53±4.47	0.69±0.02	0.78±0.02
				40-80	1.52	19.21	23.12	9.41±3.87	0.53±0.01	0.49±0.01
				>80	1.56	19.15	23.36	5.85±1.34	0.31±0.01	0.27±0.01

The experimental site was a typical compound gentle slope orchard with an average slope of 3.2°. The orchard included various fruit trees such as apple, pear and cherries trees, and the basic information regarding their species, area, and yield is listed in Table 2. The traditional whole orchard fertilization method was adopted, with fertilizers being applied only in early April and mid-to-late September. No topdressing was performed during the growth period. Surface flooding irrigation was the primary irrigation method, with irrigation quotas of 100 mm, 130 mm and 160 mm, irrigation times of 2, 2, and 3, and a single irrigation amount of 50 mm, 65 mm and 53.33 mm in wet year, normal year and dry year, respectively. Typically, irrigation was carried out after fertilization in spring and autumn and during the dry season.

Table 2 Basic information regarding the orchard

Orchard species	Yield/ (kg·hm^{-2}·a^{-1})	Area/hm^2	N uptake per 100 kg fruit yield/kg
Strawberry	45 000	2.1	0.35-0.40
Apple	33 750	2.5	0.30-0.40
Cherry	22 500	8.3	0.25
peach	22 500	2.1	0.48-0.63
Pear	30 000	2.1	0.47

2.2 Measurement and estimation of orchard N source

There are four sources of N input in orchard, namely fertilizer application, atmospheric deposition, pesticide and biological N fixation. The amount of N in orchard was calculated as follows:

$$N_{in}=N_{fer}+N_{pes}+N_{dep}+N_{fix} \quad (1)$$

where, N_{in} represents the total amount of N input of the orchard; N_{fer} represents the amount of N input by the fertilizer; N_{pes} represents the amount of N input by the pesticide; N_{dep} represents atmospheric N deposition; N_{fix} represents the amount of biological N fixation. All the units are kg/hm^2·a, which is the same below.

2.2.1 Fertilizer N application

Organic fertilizers such as poultry manure, cow manure and sheep manure were applied in the orchard. The N content of organic manure was determined by Kjeldahl method, and the fertilizer amount and N content applied in the orchard are listed in Table 3. The amount of N input from the fertilizer was calculated using the following formula:

$$N_{fer}=\sum(N_i \times P_i) \quad (2)$$

where N_i is the application amounts of different kinds of organic fertilizer; P_i represents the N content of organic fertilizer, %。

Table 3 Basic situation of organic fertilizer application

Types	Application amount/ (kg·hm^{-2}·a^{-1})	Proportion/ %	N rate/%	N amount/ (kg·hm^{-2}·a^{-1})
Poultry manure	58 140	36%	1.28±0.03	267.91±6.28
Cow manure	36 000	34%	0.38±0.02	46.51±2.59
Sheep manure	40 890	30%	0.83±0.05	101.82±7.36

2.2.2 N input of pesticides

N can also enter the orchards through the application of pesticides. Table 4 lists the types, active ingredients, application amounts, active ingredients rate and N rates of all pesticides containing N that were used in the orchard. The amount of N from the pesticide that enters the soil was calculated using the following equation:

$$N_{pes}=\sum(N_j \times I_j \times P_j) \quad (3)$$

where, N_j is the amount of pesticide applied per unit area; I_j is the content of active ingredient in pesticide, %; P_j is the N content of the active ingredient in the pesticide.

Table 4 Pesticide application details in the orchard

Name	Active ingredients	Unit dosage/ (kg·hm^{-2}·a^{-1})	Active ingredients rate/%	N rate/%	N amount/ (kg·hm^{-2}·a^{-1})
Beta-cypermethrin	$C_{22}H_{19}C_{l2}NO_3$	9.0	4.5	3.36	0.014
Deltamethrin	$C_{22}H_{19}O_3NBr_2$	3.0	2.5	2.77	0.002
Carbendazim	$C_9H_9O_2N_3$	6.0	50.0	21.97	0.659
Mancozeb	$C_{11}H_{12}O_2$	6.0	60.0	10.35	0.373
	$C_{15}H_{17}ClN_4$		2.3	19.39	0.026
Chlorothalonil	$C_8Cl_4N_2$	6.0	40.0	10.53	0.253

Note: The accuracy of active ingredients rate is ±0.1%.

2.2.3 Atmospheric N deposition

Atmospheric N deposition includes both dry deposition and wet deposition. Several researches on N deposition have been conducted in the North China Plain (NCP) and other Chinese hotspots[19,20]. Twenty-seven forests along a gradient of N deposition were measured between 22.4-112.9 kg/hm^2·a in the Beijing-Tianjin-Hebei region of Northern China[21]. Two of the monitoring points were located near Niegezhuang, with total N depositions were 58.2 and 57.4 kg/hm^2·a for the deciduous broadleaf forest of Yaowan (116°15'E, 40°38'N) and shrub of Dayanshan (116°47'E, 40°34'N), respectively (Figure 1a). The average total N disposition reached 60.6 kg/hm^2·a from 2007 to 2010 in NCP and the urban, suburban and rural N dispositions were 55.7, 50.6, and 28.5 kg/hm^2·a, respectively[22]. Two monitoring, namely Beijing (116°36'E, 39°96'N) and Yangfang (116°10'E, 40°15'N), were also located near Niegezhuang, with N depositions of (59.2±5.7) and (42.4±7.0) kg/hm^2·a, respectively (Figure 1a). The amount of atmospheric N deposition in the orchard was estimated by a weighted average of the N deposition data at the monitoring points near this orchard.

2.2.4 Biological N fixation

Biological N fixation is a process that converts N_2 into ammonia, which then participates in the N cycle in orchard[23]. Previous studies have identified several key factors that influence the rate of N fixation, including temperature, moisture, vegetation type and available N in soil[24,25]. Moreover, microbial N fixation rates are not significantly different at sites with similar conditions and latitudes[26]. Then, the amount of biological N fixation in the orchard was estimated by reviewing existing studies that have reported biological N fixation rates in forests and grasslands at the same latitude (Table 5).

Table 5 Biological N fixation rate of orchard under similar site conditions

Site name	Ecosystem type	Lone	Lat	Experimental method	N fixation rate/(kg N·hm^{-2}·a^{-1})	Reference
Big Creek Basin, Melbourne, Australia	Temperate forest	145.50	38.00	ARA	24.0	[27]
Jebo Creek, Utah, US	Temperate forest	–111.12	39.57	^{15}N	10.2	[28]
Fox Park, Wyoming, US	Temperate forest	–106.15	41.08	ARA	13.0	[29]
Lynx Prairie Preserve, Ohio, US	Grassland	–83.50	39.00	ARA	8.2	[30]

2.3 Measurement and estimation of orchard N fate

After being imported into the orchard, the fate of N can typically be categorized into three parts. Firstly, some N is exported from the orchard through runoff and sediments, while some is lost in the form of ammonia and N_2O volatilization resulting from the nitrification and denitrification effects. Secondly, a portion of N is absorbed and utilized by plants. Lastly, the remaining N disrupts the soil N balance and stays within the orchard's soil. Various methods have been used to determine and calculate the fate of N.

2.3.1 NH_3 emission

NH_3 volatilization is a major pathway for the loss of N from soil. The amount of NH_3 emission in an orchard was determined using continuous air extraction in a closed chamber[31]. NH_3 emission was measured at five selected points in the orchard within

10 d after fertilization in spring and autumn (Apr. 7 and Sep. 14) (Figure 1b). Subsequently, measurements were taken every 5-10 d until the ammonia volatilization rate stabilized. The determination was carried out at 9:00-10:00 and 16:00-17:00 each day, and the average of these two periods was calculated as the average ammonia volatilization rate of the day. Based on the average rate of ammonia volatilization after stabilization, the amount of ammonia volatilization during the non-experimental period was estimated, and the amount of ammonia volatilization in the orchard was calculated for 1 year.

2.3.2 Simultaneous nitrification and denitrification

N_2O emissions from denitrification are a crucial process in soils that can annually denitrify[32]. However, the denitrification process is affected by various factors, including soil N, carbon (C), pH, temperature, oxygen supply and water content, with soil N being a particularly significant factor[33]. Numerous scholars have conducted extensive research on the characteristics and quantify of N_2O emission under varying crops and fertilizer application rates. The relationship between fertilizer application rates and N_2O emission during the production process has been explored. Based on existing research (Table 6), there appears to be a linear relationship between N_2O emission and N fertilizer application rate[34], and the weighted average method is used to estimate the amount of N_2O emission in an orchard.

Table 6 N_2O emission rate of different orchard soils

Orchard type	N fertilizer/ (kg N·hm^{-2}·a^{-1})	N_2O emission/ (kg N·hm^{-2}·a^{-1})	Reference
Apple orchard	311.5	1.53/2.05	[35,36]
Orange orchard	Ave 597.25	1.29	[37]
Peach orchard	210	0.89	[38]
Pear orchard	500	1.68±0.61	[39]
Almond orchard	235.5	1.61±0.17	[40]

Note: The unit of N_2O emission in some original data is kg N_2O/hm^2·a, which has been converted to kg N/hm^2·a by molecular weight. Ave is the average value.

2.3.3 Runoff and sediments

N carried by runoff and sediments will somehow enter the rivers, lakes, and other water bodies, which has been proven to be a major source of non-point source pollution[41]. In the study area, surface runoff from the orchard was channeled and flowed out in the direction indicated in Figure 1b. DX-LSX-1 Doppler ultrasonic flowmeter was used to measure the concentration of runoff and sediments, while the levels of Total N in both water and soil samples were analyzed.

In 2019, 8 rainfalls events caused runoff and sediment in the orchard, and the concentration of total N was measured at inlet and outlet of the channel, as listed in Table 7.

2.3.4 Plant uptake

The growth of plant and the accumulation of fruit are strongly linked to N absorption. Numerous studies have been conducted on the optimal amount of N fertilizer required for the daily growth of commonly cultivated crops[42,43]. The quantity of N absorbed and utilized by orchard plants was estimated based on the amount of N absorbed for producing every 100 kg of fruit[16].

Table 7 Pollutant import and export concentration in the orchard

Date	Runoff/m^3	Total N concentration at inlet/mg·L^{-1}	Total N concentration at outlet/mg·L^{-1}	Amount of total N loss/kg
July 5th	2178.72	2.20±0.043	3.10±0.001	1.95±0.097
July 15th	2007.84	2.46±0.028	3.12±0.020	1.32±0.095
July 23rd	5809.92	2.11±0.028	3.62±0.005	8.77±0.194
July 25th	1537.92	1.90±0.034	2.82±0.005	1.42±0.060
July 29th	1922.40	3.17±0.048	4.12±0.022	1.82±0.135
August 4th	8031.36	5.91±0.013	7.11±0.013	9.61±0.212
August 20th	4186.56	2.05±0.004	2.97±0.008	3.87±0.053
September 10th	3246.72	2.68±0.042	3.30±0.021	2.01±0.205

2.3.5 Soil balance

N balance is an indicator used to evaluate the balance between the amount of N input and N output[10]. According to the law of mass conservation, the source of N in the orchard is equal to the sum of all its fate.

$$N_{fat} = N_{sou} \tag{4}$$

The soil N balance in the orchard could be calculated as follows:

$$N_{bal}=N_{sou} - N_{amm} - N_{run} - N_{nit} - N_{fru} \tag{5}$$

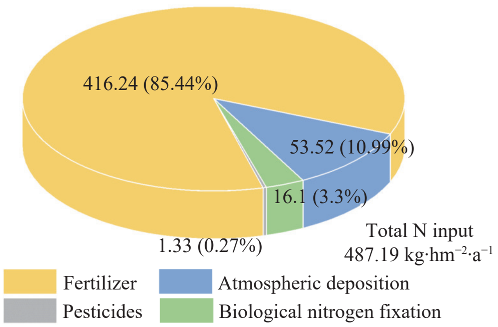
where, N_{fat} is the sum of different N fate; N_{bal} is the N surplus in soil; N_{amm} is the amount of N lost by ammonia volatilization; N_{run} is the amount of N loss carried by runoff and sediment; N_{nit} is the amount of N in soil converted to NO_x by microbial nitrification and denitrification; N_{fru} is the amount of N removed from orchard by fruit products. All unit is kg/hm^2·a.

The result of N balance can be interpreted as follows: If N balance=0, there is no N surplus in soil at an annual budget; If N balance<0, it indicates potential stress in soil, which suggests that N addition is needed to meet requirement. Conversely, if N balance>0, it indicates a potential surplus in soil[2].

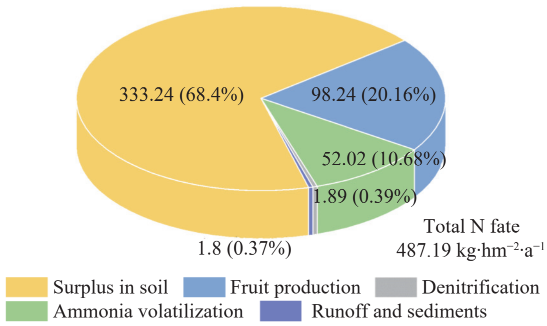
3 Results

3.1 N source and fate of the orchard

The orchard's total N input was 487.19 kg/hm^2·a, with fertilizer application, atmospheric deposition, biological N fixation and pesticide application accounting for 85.44%, 10.99%, 3.30% and 0.27% of the N source, respectively (Figure 2a). Fertilizer was the primary source of N input.



a. N source



b. N fate

Figure 2 Proportions of different components of orchard N source and fate

N output through ammonia volatilization, runoff and sediment loss, nitrification and denitrification were 52.02, 1.80, and 1.89 kg/hm^2·a, respectively, accounting for 10.68%, 0.37%, and 0.39% of N source (Figure 2b). Around 98.24 kg/hm^2·a of N was absorbed by plants and utilized for fruit production, which represented 20.16% of the N sources. The most notable finding was that there was a 333.24 kg/hm^2·a N surplus in the orchard's soil, accounting for 68.40% of N sources. This result indicates that N lost in the orchard through ammonia emission, nitrification and denitrification, runoff and sediment was relatively low, with the majority of the N input remaining in the soil as N surplus.

3.2 Uncertainty analysis

The uncertainties of the orchard's N source and fate were calculated according to the error range and method proposed above. The main error in the N source was attributed to systematic errors in fertilizer input and the random errors in atmospheric deposition and biological N fixation, estimated according to previous literature. The negligible amount of pesticide application produced an error of approximately 0. The error of N input induced by fertilizer application, atmospheric deposition, and biological N fixation was 16.23, 7.00, and 7.90 kg/hm^2·a, accounting for 3.33%, 1.44%, and 1.62% of the total N sources, respectively.

Similarly, the errors in N fate were mainly attributed to the systematic errors in the determination of ammonia volatilization, runoff and sediments loss and ammonia volatilization, and random errors in the estimation of nitrification and denitrification and fruit N content proposed by previous references. The errors in soil surplus, fruit production, ammonia volatilization, runoff, and sediment loss, nitrification and denitrification were 18.32, 5.73, 6.24, 0.06, and 0.78 kg/hm^2·a, respectively, accounting for 3.76%, 1.18%, 1.28%, 0.01%, and 0.16% of N fate.

Thus, the total error in the orchard N input was only 6.39% of the total sources. The estimated and measured errors of different components of N fate in Beijing's gentle slope orchard fell within a relatively small range of 0.01%-3.76%.

4 Discussion

4.1 N source

Excessive N input in agricultural production is a significant cause of environmental pollution[1]. According to an analysis of N source in an orchard, the total N input was 487.19 kg/hm^2·a, which was 2-3 times higher than the annual total N input in agricultural land and forest lands in Beijing and 1.5 times higher than the total N input of primary agricultural crops in China[44,45]. This indicates that the total N input in the orchard is relatively at a high level.

Fertilizer application accounted for 85.44% of N input in the orchard, which an amount about 416.24 kg/hm^2·a (Figure 2). This suggests that fertilizer application is the major source of soil N input in the orchard. The amount of fertilizer application was higher than that of traditional fertilization, with 311.5 kg/hm^2·a in Shaanxi mature orchards and 150-400 kg/hm^2·a for food crops in NCP[35,36,46]. Therefore, the orchard soils have a relatively large fertilizer application amount annually.

Numerous studies have investigated the appropriate fertilizer amounts for various orchards. Typically, applying fertilizer at rates of 250-300 kg N/hm^2·a can satisfy the requirements of trees when the orchard yield target is set at 25-30 t/hm^2·a. Moreover, research on an apple orchard planted in the Loess Plateau revealed that the most suitable fertilizer application rate for achieving a production of 35-40 t/hm^2·a was 160-200 kg/hm^2·a[42]. Other researchers suggested that commercial pear orchards often require a N application rate of 70-130 kg/hm^2·a, while strawberries usually receive a total of 80 kg/hm^2·a in U.S. farmyards. Intensive pears growing, may only require 50-60 kg/hm^2·a to maintain good fruit quality and production[47,48]. These findings demonstrate that different locations, fruit types and fruit yield targets can influence the optimal fertilization amount. Nonetheless, application rates of 50-300 kg N/hm^2·a can meet almost all the fertilization requirements of different fruit trees and conditions.

If the N fertilizer application rate in the orchard was reduced from 416.24 to 300 kg/hm^2·a, the corresponding soil N surplus would be decrease from 333.24 to 200 kg/hm^2·a, resulting in a one-third reduction in soil N surplus. Moreover, decreasing the fertilizer application rate from 416.24 kg/hm^2·a to 100 kg/hm^2·a would lead to N input being consistent with N consumption and loss, meaning that the N element in the orchard would maintain balance and have minimum negative impact on the environment. Therefore, a reasonable fertilization rate of 100 kg N/hm^2·a could be adopted for Beijing typical orchard. This research also indicates that the current N fertilization amount could meet the orchard's demand for four years. Consequently, it may be appropriate to consider reducing or discontinuing the application of N fertilizer in the next 2-3 years.

4.2 N fate

4.2.1 Distribution and migration of N in soil

The accumulation and migration of N to the deep soil layer is the primary cause of groundwater pollution[13]. This research found a N surplus of 333.24 kg/hm^2·a in the orchard soil, which accounted for 68.40% of the N input (Figure 2b). To further examine the distribution and migration of accumulated N in the soil, the study area was divided into 30 grids and measured the soil N content of the 0-40 and 40-80 cm soil layers before and after the fruit tree growing season in each grid (Figure 1b). Then, the changes of N in different soil layers of 0-40 cm, 40-80 cm and >80 cm before and after the growing season were calculated based on the principle of mass conservation. This calculation represented the amount of N migration in the soil, except for plant absorption and utilization. The variation of N in different soil layer before and after growing season was computed using the following equations:

$$N_{\mathrm{vari}} = N_{\mathrm{auti}} - N_{\mathrm{spri}} \tag{6}$$

$$N_{>80} = N_{\mathrm{bal}} - \sum N_{\mathrm{vari}} \tag{7}$$

where, N_{vari} is the variation of N in different soil layers before and after growing season; N_{auti} is the residual N in different soil layers in autumn; N_{spri} is the background value of N in different soil layers in spring; $N_{>80}$ is the variation of N under 80 cm soil layer.

According to Equations (6) and (7), the N surplus in the 0-40 cm, 40-80 cm, and >80 cm soil layers were 176.72, 99.00, and 57.52 kg/hm^2·a, respectively, accounting for 53.03%, 29.71%, and 17.26% of the total N surplus. Therefore, the majority of the N surplus was found in 0-40 cm soil layer, followed by 40-80 cm and >80 cm soil layers.

An excessive N surplus in the surface layer can contribute to secondary salinization of soil, which can negatively impact for crop growth and nutrient absorption[49]. Additionally, excessive N accumulation in the 40-80 cm soil layer can lead to N enrichment in plants and a high nitrate content in fruits, resulting in reduced fruit yield, quality and safety[50]. Furthermore, leaching of N to deep soil layers is a significant pathway N movement and can cause groundwater pollution[51]. Therefore, it is crucial to reduce N accumulation in the soil surface, promote N absorption and utilization by plants, and prevent N migration to groundwater.

The N surplus in the surface soil of the orchard at 0-40 cm may be attributed to two reasons. Firstly, the organic fertilizer used in the orchard has a slow-release rate of effective nutrients, limiting the absorption and utilization of N by plants, resulting in the accumulation of N in the soil surface[52]. Secondly, it may be due to the high level of N on the surface soil resulting from fertilization throughout the orchard[53]. Whole orchard fertilization is a traditional agricultural management measure more suitable for planting field crops with high density, small row spacing, and shallow root system. However, the arbor and shrub species planted in orchard have small planting density, large row spacing, and deep root system, which are more suitable for circular furrow fertilization[54].

Soil surface N accumulation provides favorable conditions for the migration of N to the deep layer. Further studies have shown that 99.00 kg/hm^2·a of N migrated to the 40-80 cm soil layer, which is approximately equal to the amount of N absorbed and utilized by plants in the orchard annually. The root systems of shrub and arbor species in orchards are mainly concentrated in the 40-60 cm and 50-80 cm soil layers[24,55]. This means these N could meet the demands for N absorption and utilization of fruit trees in next year. It also verified that the current fertilization rate could meet the N demands of fruit trees for more than two years.

The amount of N that migrated to the soil layer below 80 cm in the orchard could reach up to 57.52 kg/hm^2·a. As there is less distribution of roots below 80 cm, N in this layer is hardly absorbed and utilized by plants, which might pose the main risk of groundwater pollution. Therefore, reducing the amount of N migration from the soil surface to the deep soil layer (>80 cm) and promoting the migration to 40-80 cm for plants to absorb can be an effective way to reduce groundwater pollution.

Natural precipitation and irrigation water are considered the main power sources and carriers of N migration from the soil surface to the deep layer in the orchard[10]. According to the frequency calculation and wiring method, the annual precipitation in the study area during 1999-2018 for wet year (25%), normal year (50%) and dry year (75%) was 371.10, 480.60, and 576.20 mm, respectively. The precipitation in Beijing was 497.45 mm in 2019, indicating a normal year, and thus the irrigation quota was 130.00 mm. After each fertilization, irrigation was performed with a value of 65.00 mm. In total, 627.45 mm of water entered the soil in a year. According to Zhang et al.[56], the mean annual evaporation for mountain vegetation was around 600.00 mm, and 115.00 mm was a reasonable but inefficient irrigation amount for suburban farmland in Beijing. This indicates that the orchard's irrigation quota was basically reasonable and could meet the needs of fruit tree growth and transpiration while achieving a basically balanced water budget. Therefore, the irrigation schedule and method might be the reason for the N migration to the deep layer because it provided enough power to promote the migration.

The initial soil water content and field water capacity of the orchard were used to estimate the depth of planned wetting soil layer after a single irrigation in a wet year, normal year, and dry year under the traditional irrigation schedule (Table 1). The results indicated that the depths would be 61 cm, 85 cm, and 66 cm, respectively. In a normal year, a single irrigation would provide enough soil water to distribute nutrients to the deep soil layer, leading to the migration of N below 80 cm in the orchard soil. To mitigate this issue, it is recommended to reduce the amount of single irrigation and increase the frequency of irrigation to three times for normal years. This adjustment would result in a planned depth of soil wetting layer after irrigation of 50 cm, effectively reducing the amount of N migration to the deep layer.

In addition to the unreasonable irrigation schedule, another reason for the downward migration of N in orchards was use an unreasonable irrigation method. Traditional surface flood irrigation, which was used in the orchard, had several problems such as difficulty in controlling irrigation quota, serious waste of water resources, low irrigation uniformity and soil compaction. Fortunately, these issues can be significantly improved by adopting high-efficiency water-saving irrigation technology. This not only greatly liberates labor force but also improves water use efficiency[57-59]. Currently, among the high-efficiency water-saving irrigation technologies, drip irrigation and small-pipe outflow are suitable for directly irrigating the soil surface near the roots of trees such as arbor and shrub species, especially for orchard irrigation[60]. Moreover, drip irrigation and small pipe outflow technology can effectively reduce surface evaporation, finely control the amount of irrigation water, and save 30%-50% of water compared with flood irrigation[61,62]. Therefore, by adopting appropriate irrigation schedules and high-efficiency water-saving irrigation techniques, the threat of groundwater pollution caused by the migration of N to deep layers can be effectively reduced.

4.2.2 Plant uptake and utilization

The most desirable fate for N is uptake and utilization for crop production. The N fertilizer use efficiency (NUE) in the orchard can be calculated using the following equation:

$$\mathrm{NUE}=\frac{\text{N plant uptake}}{\text{N fertilizer}} \tag{8}$$

where, N plank uptake represents the amount of N absorbed and utilized by orchard plants; N fertilizer represents the amount of N fertilizer applied in the orchard.

The NUE of this orchard was only 23.59%, which was much lower than the average NUE (30%-35%) in China prescribed by the World Health Organization. Furthermore, this value was lower than the crop N uptake rates of 43% in the agroecology system of NCP proposed by Liu et al.[63]. One possible reason for the relatively low NUE was the excessive fertilization in the orchard. Since field crops are mostly annual crops, the absorption and utilization process of N are involved in the entire plant growth and reproduction cycle, and N is the most abundant nutrient in the grains of field crops. These factors lead to a relatively larger NUE for field crops. Therefore, reducing the fertilizer application amount is the primary method to improve the NUE of the orchard. As mentioned earlier, when the fertilization rate is reduced to 100 kg/hm^2·a, the NUE of the orchard will increase to over 90%.

4.2.3 N loss

After analyzing N fate in the orchard, it was found that ammonia volatilization, N_2O emission and runoff and sediment loss were the main pathways of N loss. Among these, ammonia volatilization was the major pathway of N loss in the orchard, which is consistent with the findings of previous studies[64,65]. Reducing soil ammonia volatilization and inhibiting N_2O emission are effective methods to mitigate N loss in soil and alleviate environmental pollution. Substituting 50% of pig and chicken manure for chemical N fertilizer could mitigate N loss by approximately 42.8%-48.1% in the NCP[46]. Adding biochar and nitrification inhibitors amendments could reduce NH_3 and N_2O emissions in field soil and enhance the NUE[66-69]. These methods can be all tried to reduce NH_3 and N_2O emissions in orchards.

N loss from orchard soil surface runoff and sediments is one of the primary sources of non-point source pollution[70]. However, N carried by runoff and sediments accounted for only 1.80 kg/hm^2·a in orchards with a gentle slope, which was only 0.37% of N fate (Figure 2b). The portion of N fate would eventually flow into the Jingmi diversion canal with a flow rate at 1.89-2.21 billion m^3/a after leaving the orchard. The confluence flowing area was mainly located in Haidian District of Beijing and covered about 1644.63 hm^2[71]. Thus, it was estimated that the N loss caused by the orchard ranged from 0.0014 to 0.0016 mg/L, indicating that N loss from orchards on gentle slopes had a negligible impact on non-point source pollution. It is worth nothing that orchards in many regions are situated in mountainous and hilly areas, with relatively steep slope gradients. Research has demonstrated that under identical rainfall conditions, the sediment yield on the slope increases significantly with an increase of slope gradient when the slope gradient is smaller than the critical slope[72]. The sediment yields will attain the maximum value at the critical slope and then decrease with an increase in slope gradient. The maximum erosion rate at the critical slope can be 40-50 times that at the gentle slope (3°-5°), whereas the slope has little impact on runoff[73,74]. Therefore, we estimated that N loss with runoff and sediments in orchards with steep slopes was around 15.83-19.43 kg/hm^2·a, accounting for only 3.6% of orchard N input. Even in orchards with steep slopes, the change in N content was 0.05-0.08 mg/L, which was significantly greater than that caused by orchards with gentle slopes. However, considering that the total N content of class I of surface water should be lower than 0.2 mg/L, the N output caused by runoff and sediment loss in these orchards remained at a low level, indicating that slope had little effect on N loss in orchards. Furthermore, if the fertilizer application amount were reduced to 100 kg N/hm^2·a, the N loss through runoff and sediments would be reduced by approximately 80%. Since the N surplus in the soil could meet the N demand of plants, the amount of fertilizer was reduced or not applied in the second to third year. Consequently, N loss through runoff and sediment would hardly contribute to non-point source pollution.

5 Conclusions

This study provides a quantitative analysis of N sources and fate in an orchard. The total N input was 487.19 kg/hm^2·a, with fertilizer application being the main source and accounting for 85.44% (416.24 kg/hm^2·a) of the total N input. Atmosphere deposition, biological N fixation and pesticides of N source were relatively minor N sources, accounting for 10.99% (53.52 kg/hm^2·a), 3.30% (16.10 kg/hm^2·a) and 0.27% (1.33 kg/hm^2·a), respectively. However, the N fertilizer application amount of 416.24 kg/hm^2·a was much higher than the requirement for plant growth, resulting in soil N surplus and low NUE in the orchard. A reasonable N fertilization rate for Beijing orchards would be 100 kg/hm^2·a, which can satisfy the orchard's demand for four years. Reducing or stopping N fertilizer application in the next two or three years could be considered.

The N fate in the orchard showed that the N surplus in the soil and the amount absorbed by fruit trees were 333.24 kg N/hm^2·a (68.40%) and 98.24 kg N/hm^2·a (20.16%) respectively. N was lost through ammonia volatilization, N_2O emission and runoff and sediments, which accounted for 52.02 (10.68%), 1.80 (0.37%), 1.89 (0.39%) kg N/hm^2·a, respectively. The N input of the orchard mainly remained in the soil, while N loss occurred mainly via ammonia volatilization. The N surplus in the soil retained in 0-40 cm, 40-80 cm, and >80 cm soil layers was about 36.27%, 20.32%, and 11.81% of N input in the orchard. It has been concluded that the accumulation of large amounts of N surplus on the soil surface, combined with the uptake of N that is not timely during N migration process, could lead to environmental pollution risks in orchards. To effectively reduce the migration of N from soil surface to deep layer of orchards, it is advisable to reduce N fertilizer application and adjust the irrigation schedule by decreasing the amount of single irrigation and increasing the frequency of irrigation to three times in a normal year. And adopting efficient water-saving irrigation technology is a practical method to deal with N accumulation on the soil surface.

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