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Effect of bag-controlled release fertilizer on nitrogen loss, greenhouse gas emissions, and nitrogen applied amount in peach production

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A B S T R A C T

In common nutrient management in peach orchards in China, a large amount of nitrogen fertilizer is used. However, low nitrogen absorption and utilization rate results in nitrogen loss and greenhouse gas emissions, which is not favorable for cleaner production in peach orchards. In this experiment, nitrogen leaching, ammonia volatilization, greenhouse gas emissions under bag-controlled release fertilizer (BCRF) were evaluated. In addition, the impact of BCRF on soil nutrient status in peach orchards, peach root system growth, nitrogen absorption and utilization rate, fruit quality, and the potential for using BCRF in major peach-producing areas in China to reduce the amount of nitrogen fertilizer application were also investigated. Results showed that BCRF maintained a stable supply of nutrients to soil, decreased nitrogen leaching, ammonia volatilization and greenhouse gas emissions while nitrogen loss was significantly reduced from peach orchard soil. Also, BCRF reduced the combined global warming potential at 20-, 100-, and 500-years. A 5-year study revealed that application of BCRF promoted the formation of a dense root system in peach trees by the development of fine roots and a more concentrated root distribution. This extended the lifespan of the root system and improved fruit quality. ^{15}N tracer experiments showed that BCRF significantly increased the absorption and utilization rate of nitrogen by peach trees. BCRF reduced the amount of nitrogen fertilizers applied by 65–82% compared to common fertilizer application methods without decreasing peach yield, so it has huge potential for reducing the amount of nitrogen fertilizer used as well as fertilizer input costs in peach production. The results showed that BCRF has huge application potential as a new, environmentally friendly, low-cost, and efficient fertilizer for cleaner production in peach orchards.

1. Introduction

The amount of nitrogen fertilizer consumed in China accounts for 30% of total global consumption. However, the utilization rate of nitrogen fertilizer is only 30–40% (Zhu, 2000). Globally, it is estimated that the amount of nitrogen fertilizer consumed will increase to 13×10^9–15×10^9 t/y in 2050 (Matson et al., 1998). Low fertilizer utilization rate is a common problem when chemical fertilizers were used. Among chemical fertilizers, nitrogen loss is particularly serious. Nitrogen use efficiency (NUE) has decreased during the past two decades, with much of this excess nitrogen fertilizer being lost to the environment (MOA, 2007; National Bureau of Statistics of China, 2013). This not only results in direct economic losses but also environmental pollution in some cases when fertilizer application is improperly applied. This causes surface water eutrophication, nitrate nitrogen levels in groundwater exceeding standards, and increased N_2O emissions (Zhu, 2000). Direct application of urea into soil will result in rapid hydrolysis and a large loss of nitrogen due to surface runoff, leaching, and volatilization and low absorption and utilization rate of nitrogen fertilizers, resulting in serious environmental pollution problems (Salvagiotti et al., 2008; Pereira et al., 2017; Wang et al., 2004). In addition, the emission of greenhouse gases, e.g. N_2O, is also an important cause of nitrogen loss following fertilizer application (Pereira et al., 2015), which is not favorable for clean production in

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peach orchards.

Common fertilizer, owing to the low thermal stability, high solubility and small molecular weight, tends to migrate into the air and water through volatilization, runoff and leaching, causing severe environmental pollution such as acid rain, eutrophication and global warming (Mclsaac et al., 2001; Erisman et al., 2008; Guo et al., 2010; Reay et al., 2012). Global warming caused by greenhouse gas emissions has attracted widespread attention, particularly from scientists who are committed to cleaner production. N_2O produced during nitrification-denitrification is an important greenhouse gas, and its global warming potential (GWP) is 298 times that of the reference gas, CO_2. In addition, N_2O can damage the ozone layer and threaten human health. In agricultural cultivation systems, the continuous increase in the amount of chemical fertilizers applied causes N_2O and CO_2 emissions to be the largest sources of greenhouse gas emissions (IPCC, 2014). As the largest consumer of nitrogen fertilizer, China accounts for 36% of global fertilizer usage (Hvistendahl, 2010) and 20% of agricultural N_2O emissions globally (World Bank, 2014). Further, excessive application causes low nitrogen fertilizer utilization rate, which not only wastes resources and increases production costs but also reduces air and soil quality and causes water pollution (Goulding et al., 2008). Reports from both China and abroad have noted a lower seasonal utilization rate of nitrogen fertilizers in fruit trees, at only 10%–15% (Jastrow, 1996). The amount of residual nitrogen in deep soil layers in orchards is higher than field crops (Lv et al., 1998). Thus, quantifying the rapidly increasing nitrous oxide emission from excessive nitrogen fertilizer input is a pressing demand for reducing greenhouse gas in cleaner agricultural production (Zhang et al., 2016).

Peach tree is the fourth largest fruit crop grown in China, with a cultivated area of more than 1 million hectares. China's peach cultivation area and total output account for 50% of the world's total, which are the highest in the world. Most peach orchards in China are located in mountainous, hilly, and coastal areas, which have a thin soil layer, low organic matter content (less than 1.5 g kg^{-1}), non-uniform nutrients, and poor water and fertilizer retention capabilities. Also, soil management mainly involves clean tillage in most orchards, which leads to soil organic matter content being difficult to improve. Application of organic fertilizer can effectively increase soil organic matter content. However, the effect of organic fertilizers on yield is slow and variable in the short term (Khaliq et al., 2006). The use of organic fertilizers needs more labor and monetary input to compare with the use of chemical fertilizers (Maggio et al., 2008; Wang and Zhang, 2013; Hu and Yang, 2015). Most farmers in China have to use chemical fertilizers instead of organic fertilizers, mainly due to they fear that they may lose income if they switch to organic fertilizers (Wang et al., 2018) especially with the labor cost increasing rapidly in China. The problem of high utilization amount of chemical fertilizers and insufficient input of organic fertilizer in orchards in China is widespread. As a result, a large amount of fertilizer must be applied to peach orchards to ensure yield and economic benefits, which results in nitrogen loss, greenhouse gas emissions, and a decrease in the soil quality of peach orchards, and it is not conducive to the formation of fruit quality.

Through our investigation, in common nutrient management in peach orchards in China, a large amount of nitrogen fertilizer is used—reaching 337.43 kg N ha^{-1} yr^{-1} (Data not published). However, the nitrogen absorption and utilization rate is low, which is not favorable for sustainable development of peach orchards. Under multiple pressures, such as global resource depletion and environmental degradation, the best use of green fertilizers to effectively improve nitrogen absorption and utilization efficiency and reduce the amount of fertilizer application to avoid resource, environmental, and agricultural product safety problems caused by excessive fertilizer application has been a topic of interest around the world. In addition, excessive application of nitrogen fertilizer is not conducive to fruit quality formation and food safety.

Nitrogen loss from fertilizers is associated with climatic conditions, soil characteristics, and type of fertilizer (Bouwman et al., 1997; Abalos et al., 2014; Faostat, 2014). Among these factors, only the type of fertilizer is easily controlled. The most coated slow/controlled-release fertilizer products use a polymer coating on the surface of urea granules to decrease the dissolution rate of urea (Cao et al., 2009; Lyu et al., 2015) and reduce nitrogen loss. In addition, soil amendments play a good role in reducing nitrogen loss, e.g. biochar which refers to a black, dusty, alkali and highly porous product of lignocellulose pyrolysis has been proven to be a good soil improver and sorbent of nutrients (Maroušek et al., 2017b). Maroušek et al. (2017a, 2018) reported that use of biochar for nitrogen fertilization accelerates metabolism of soil biota, turning more nitrogen from fertilizers into organic forms as a result. The results of their study indicate that use of biochar for nitrogen fertilization can case sorption of nitrogen into highly porous substrate which allows the possibility of reducing nitrogen leaching and volatilization. However, the high price of coated slow/controlled-release fertilizer makes it impossible for widespread application in peach orchard production.

In recent years, our research team has developed a new environmentally friendly bag-controlled release fertilizer (BCRF). We have taken advantage of the inherently large size of the fruit trees to change the design of slow-release fertilizers. Instead of common granular coated fertilizers, paper-plastic composite bags were used to allow for controlled release of regular fertilizers. We carried out systematic research on BCRF, conducted five continuous years of tests in a demonstration peach orchard, and established a fertilization technology model for reducing fertilizers and increasing the efficiency of fertilizers. The technology model has been widely promoted and applied. It can greatly reduce the amount of chemical fertilizer application in peach producing areas.

The purpose of the study was to evaluate the impact of BCRF on soil nitrogen leaching, NH_3 volatilization, and combined global warming potential. Further, we examined the impact of the application of BCRF for five continuous years on soil nutrient status in peach orchards, peach root system growth, nitrogen absorption and utilization rate in peach trees, and quality of peach fruit. We also investigated the potential of BCRF in reducing the amount of nitrogen fertilizers used in peach producing areas. The ultimate goal is to develop environmentally friendly new fertilizer product for the cleaner production of peaches.

2. Materials and methods

2.1. Preparation of BCRF

The bag is made of a paper-plastic composite material, as referred refer to in our patented product (Peng et al., 2007). The selected paper-plastic composite material contains 50 g of paper and 15–20 g of polyethylene. First, a puncher was used to make holes in the material. The rows of micro-holes were uniformly distributed on both sides of the bag. The diameter of the micro-holes was 0.2 mm, and the distance between micro holes was 0.5 cm. The bag is shown in Fig. 1. Afterwards, the paper-plastic composite material was placed on the granular packager. The fertilizer in the bags consists of urea, diammonium hydrogen phosphate, and potassium sulfate in a ratio of 41:14:40 ($N:P_2O_5:K_2O$). After mixing, the composite fertilizer was packaged into the bags through the granular packager. The bags were 9 cm wide and of 15 cm long (95 g/bag, BCRF). The bags were filled with the fertilizer

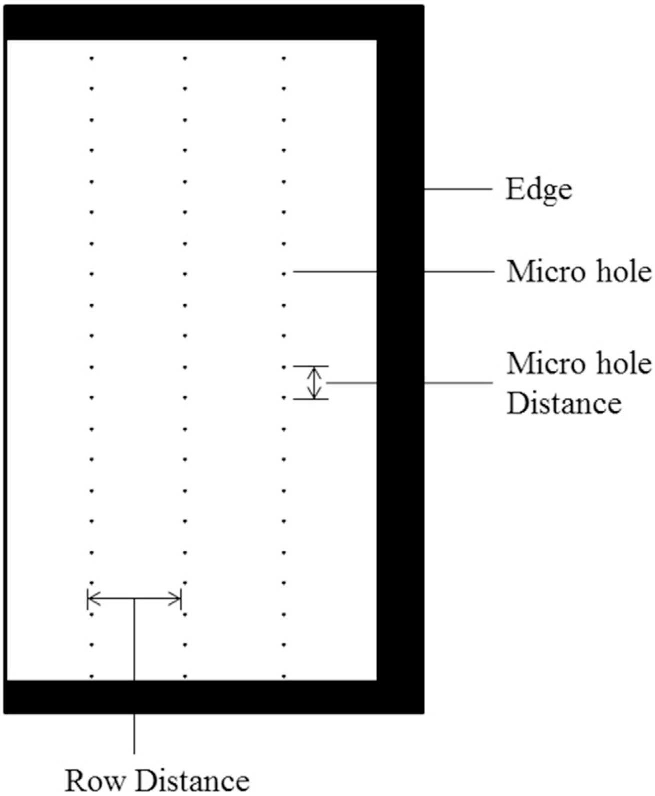

Fig. 1. Bag of bag-controlled release fertilizer.

until they were full.

2.2. Effects of BCRF on soil nitrogen distribution, nitrogen leaching, NH_3 volatilization and greenhouse gas emissions from the soil

This study in this paper was conducted at the Gardening Test Station of Shandong Agriculture University, 7 Panhe Street, Tai'an district, Tai'an, China. In order to examine the effects of BCRF on NH_3 and greenhouse gas emissions from the soil in the peach orchard, simulation experiments were set up. A single factor random block design was employed for the experiment, and three treatments were set up: BCRF (95 g/bag, 2 bags with ordinary composite mixed fertilizer: Urea, diammonium hydrogen phosphate, and potassium sulfate in a ratio of 41:14:40 ($N:P_2O_5:K_2O$), ECF (equal amount of common composite fertilizer: Fertilized with an equivalent amount of composite fertilizer mixed in the same ratio of $N:P_2O_5:K_2O$ as the BCRF), and no fertilizer application (Control). Each treatment was performed in triplicate. For the ECF treatment, the fertilizer was placed inside a nylon mesh bag. The fertilizers were placed flat on the mesh bag, and the size of the mesh was such that the coated fertilizer inside the bag did not come out. Soil layers at a depth of 0–50 cm from empty land in the orchard were collected. After sieving, they were packed into 80 cm × 100 cm (diameter × height) plastic cylinders. Each cylinder contained 300 kg of soil. The total amount of fertilizer applied was 43.64 g m^{-2} based on pure nitrogen under BCRF and ECF treatment. The fertilizer was buried in a container at a depth of 5 cm. At the start of the experiment, the soil water content was maintained at 80% of the soil water holding capacity. The amount of NH_3, N_2O, and CO_2 released under different treatments was measured.

To study the effect of BCRF on soil nitrogen distribution samples were collected on Days 10, 50, and 90 after fertilizer application. Soil samples were taken from the locations under and near where the fertilizer bag had been applied. Three sampling points were selected, set up horizontally from the fertilizer application point using the boundary of the fertilizer bag as a limit. Soil samples were collected at 0–2 cm, 2–4 cm, and 4–6 cm from the boundary of the fertilizer bag. In addition, six sampling points were selected, set up vertically from the fertilizer application point. Soil samples were collected at 2- cm intervals, which were 0–2 cm, 2–4 cm, 4–6 cm, 6–8 cm, 8–10 cm, and 10–12 cm under the fertilizer bag. The levels of total nitrogen (N), nitrate nitrogen, and ammoniacal nitrogen in soil samples were measured.

To study the effect of BCRF on nitrogen leaching, we artificially added water to different treatments to simulate rainfall and study the effects of rainfall on nitrogen leaching. To a bucket, 45 L of water was added so that soil moisture reached the water holding capacity of the field. After 1 day of culture, 18 L of water was added so as to cause leaching, and the leachate was collected. After leaching, a plastic film was used to cover the plastic bucket in order to avoid the effects of rainfall. Leaching was carried out on Days 2, 7, 12, 17, 22, 27, and 31 of culture and the leachate was collected after every leaching treatment. During the experiment, a total volume of water of 175 L was added. After the leaching process was completed, soil samples from depth ranges of 0–10 cm, 10–20 cm, and 20–30 cm were collected. The levels of ammoniacal N, nitrate N, Ca^{2+}, Mg^{+}, K^{+}, Na^{+}, as well as the soil pH and conductivity were measured in the soil samples.

2.3. Effects of BCRF on soil nutrient status in peach orchard, peach root system growth, nitrogen absorption and utilization rate, and fruit quality in peach trees

In order to study the effects of continuous application of BCRF on soil nutrient status, root system growth, yield, and quality in the peach orchard, the experiment was carried out for five continuous years (2012–2016). The variety was “Ruipan No. 21”. One-year-old peach trees were planted beginning in 2012; the maturation period of this variety in the Tai'an region was late September. The three experimental treatments were BCRF (95 g/bag, bag with ordinary composite mixed fertilizer: Urea, diammonium hydrogen phosphate, and potassium sulfate in a ratio of 41:14:40 ($N:P_2O_5:K_2O$)), FSA I (equal amount ditch application once: with equivalent amount of ordinary fertilizer, mixed in the same ratio as the BCRF), and HFSA II (high-dose double ditch application twice: with double amount of ordinary fertilizer, mixed in the same ratio as the BCRF). The HFSA II is a widespread fertilizer application method used by farmers during production. Three plots were set up for each treatment, and each plot contained six trees. Fertilizers were applied using the radial ditch method, i.e. radial ditches were dug at a distance of 30 cm from the trees. The ditches were 15–20 cm wide, 20–30 cm deep, and 20–30 cm long. The BCRF was placed into the radial ditch and the upper part of the soil was covered. Composite fertilizer and soil were mixed and backfilled into the radial ditch. From 2014 onwards after fruit bearing, the amount of fertilizer applied for the HFSA II treatment was doubled and the length of the radial ditches was 40–60 cm. Table 1 shows the fertilizer application timeline.

The ditch application treatment was an equivalent amount of composite mixed fertilizer as BCRF was spread within the ditches. In 2016, 0.5 g of ^{15}N urea (produced by Shanghai Research Institute of Chemical Industry Co., Ltd., with an abundance of 10.35%) was used to replace 0.5 g of ordinary urea in every bag in the BCRF treatments; 5 g of ^{15}N urea was used to replace 5 g of ordinary urea in the FSA I treatments for mixed application; and 10 g of ^{15}N urea was used to replace 10 g of ordinary urea in the HFSA II treatments for mixed application. Three trees were randomly selected from every treatment in the middle of April, July, and October every year.

Table 1
The fertilization dates and amounts.

Treatments	2012/4/1	2013/3/1	2014/3/1	2014/6/1	2015/3/1	2015/6/1	2016/3/1	2016/6/1
	Number of radial ditches × Amount of bag-controlled release fertilizer (bag/ditch)							
BCRF	2 × 1	4 × 1	4 × 2		5 × 2		5 × 2	
FSA I	2 × 1	4 × 1	4 × 2		5 × 2		5 × 2	
HFSA II	2 × 1	4 × 1	4 × 2	4 × 2	5 × 2	5 × 2	5 × 2	5 × 2

The fertilizer application zones were avoided, and soil layer samples were randomly collected at depths of 0–20 cm and 20–40 cm. After natural air-drying, nutrient measurement was carried out.

As peach trees have large root systems with wide distribution, it is difficult to collect samples. Therefore, root samples were collected by sectional digging. On 1 November 2016, three trees were randomly selected for each treatment. The tree trunk was used as the center and segments were set up at every 20 cm at the horizontal direction between rows. Square holes measuring 50 cm × 20 cm × 40 cm were dug at each segment until no roots appeared. The peach tree roots at every segment were labeled and packed in self-sealing bags before they were brought back to the laboratory. The root samples were washed and dried. The WinRHIZO fully automated root system scanner was used for scanning and analysis of the root system. In this study, fine, small, medium, and large roots were defined as $d \le 2$ mm, $2 \text{ mm} < d \le 5$ mm, $5 \text{ mm} < d \le 10$ mm, and >10 mm, respectively.

After the trees had borne fruit (2014), the fruit quality was counted (2016), and five fruits were collected from the middle to top of the tree canopy for each tree, for a total of 30 fruits. These fruits were brought back to the laboratory for measurement of fruit quality. Titratable acidity was measured using acid-base titration. Soluble sugars in fruits were measured using anthrone colorimetry. Soluble solids were measured using the TD-45 saccharimeter.

Samples were collected from all parts of the peach trees that were labeled with ^{15}N urea for analysis on 20 September 2016 (fruit maturation period). The tree was divided into six parts, namely leaves, lateral branches, main trunk, thick roots (diameter >2 mm), fine roots (diameter ≤2 mm), and fruits. Following that, every sample were washed using clean water, detergent, clear water, 1% hydrochloric acid, and three times with deionized water. After that, the samples were fixed at 105 °C for 30 min. Subsequently, the samples were dried to constant weight at 80 °C, ground, passed through a 0.147-mm sieve, and mixed before packaging into bags for subsequent experiments. Total nitrogen content of the samples was measured using the Kjeldahl method (Bao, 2000). ^{15}N abundance was measured using a MAT-251 mass spectrometer (Institute of Food Science and Technology, CAAS).

Nitrogen utilization rate equations:

Ndff= (^{15}N abundance in plant sample−^{15}N natural abundance)/(^{15}N abundance in fertilizer−^{15}N natural abundance) × 100%.

Nitrogen utilization rate = [Ndff × total nitrogen content of organ (g)]/amount of fertilizer applied (g) × 100%.

2.4. Analysis of the potential of reducing application of nitrogen fertilizers when BCRFs were used in major peach-producing areas in China

We surveyed peach farmers who employ common fertilizer application methods (application of ordinary composite fertilizer) in major peach-producing areas in China on the amount of chemical fertilizers used every year for nutrient management during the full fruiting period. There were 106, 62, 76, 21, 26, and 31 farmers surveyed from Shandong, Hebei, Henan, Liaoning, Shaanxi, and Gansu provinces, respectively, which were also the locations of the demonstration orchards. We surveyed the amount of chemical fertilizers used when the BCRF were used in the demonstration orchards, of which 10, 4, 3, 4, 3, and 3 orchards were located at Shandong, Hebei, Henan, Liaoning, Shaanxi, and Gansu provinces, respectively. Further, we investigated the yield of different farmers (peach varieties were divided into early, middle, and late maturation varieties according to their maturity period), compared the differences in the amount of fertilizers applied between BCRF and common fertilizer application methods, and analyzed the potential of BCRF in reducing the amount of nitrogen fertilizer application.

2.5. Measurement of amount of nutrients

Soil ammoniacal nitrogen and nitrate nitrogen was measured using the QuickChem FIA+8000 Series flow injection analysis system (Lachat Instruments, Loveland, CO, USA). The alkaline hydrolysis diffusion method was used to measure available nitrogen content. Sodium bicarbonate extraction-molybdenum antimony reverse colorimetry was used to quantitate available phosphorus content. Ammonium acetate extraction-flame photometry was used to measure available potassium content (Bao, 2000).

2.6. Collection and measurement of NH_3 gas

NH_3 gas was collected according to the method of Kissel et al. (1977) and Zhu et al. (1985) with some improvements. A plastic box with an internal diameter of 30 cm and height of 40 cm was inverted in the center of the fertilizer application site and driven 5 cm into the soil. The plastic box was connected to a plastic box containing 200 mL of 2% boric acid and indicator. The sketch of NH_3 absorption is shown in Fig. 2. Every day, the boric acid was changed at 9–11 a.m. and the NH_3 absorbed by the boric acid was measured. NH_3 samples were collected every day in the first 30 days, followed

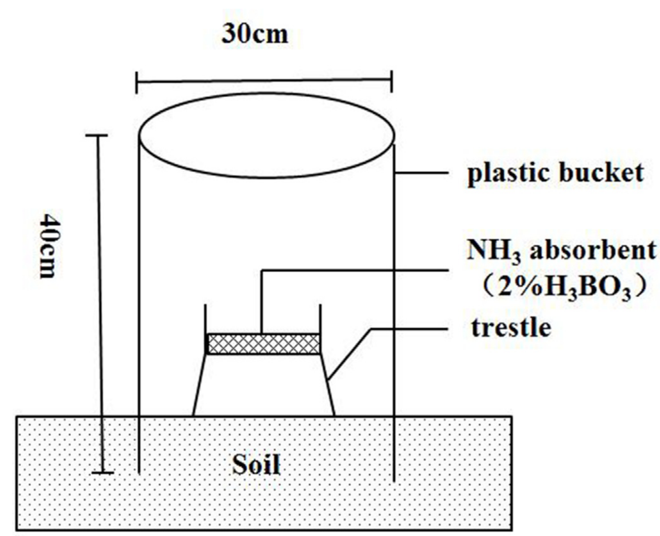

Fig. 2. The sketch of NH_3 absorption.

by once every 5 days for a total of 49 samplings in 125 days. Sulfuric acid titration at 0.005 mol L^{-1} was used to measure the NH_3 absorbed by the boric acid (m_i). Soil volatilization rate and cumulative soil NH_3 loss by volatilization were calculated as follows:

Soil volatilization rate ($mg \cdot d^{-1}$) = mean soil NH_3 volatilized measured for each collection (mi)/continuous capture duration in every sampling (d), in which the d in the first 30 days was 1 and the d after Day 30 was 5.

Cumulative soil NH_3 volatilized (mg) = $m_1+m_2+ \ldots +m_i$

2.7. Collection and measurement of N_2O and CO_2

N_2O and CO_2 were collected using the sealed static box method as described by Li (2010) and made some improvements. The box was a cylinder with an internal diameter of 30 cm and height of 40 cm which was inverted in the center of the fertilizer application site and driven 5 cm into the soil. The collection sketch of N_2O and CO_2 is shown in Fig. 3. Gases in the sealed box were collected at 0 and 30 min and 30 mL of samples were collected each time and stored in a 20 mL vacuum glass bottle (Inselsbacher et al., 2011). N_2O, and CO_2 were collected at 9 a.m.–11 a.m., and 12 samplings were carried out within 1 month after fertilizer application.

Quantitation of N_2O (CO_2): Gas chromatography via a gas chromatography system (HP7890), detection device (electron capture detector), detection temperature (330 °C), chromatography column (Porpak Q), column temperature (70 °C), carrier gas (pure N_2), and flow rate (25 L min^{-1}). The c s were calculated (Zheng et al., 1998).

Calculation of N_2O (CO_2) emission flux:

$F = \Delta m/(A \times \Delta t) = (m_2 - m_1)/(A \times \Delta t)$.

$= [C_2 \times V \times M_0 \times 273/(273 + T_2) - C_1 \times V \times M_0 \times 273/(273 + T_1)]/[(A \times (T_2 - T_1) \times 22.4]$, where F is N_2O emission flux ($mg \cdot m^{-2} h^{-1}$), in which a positive value means emission while a negative value means absorption; A is the bottom area of the sampling box, (m^2); V is the area of the sampling box, (m^3); m_1 and m_2 are the mass of N_2 in the sampling box before sealing and before opening, respectively, (g); t_1 and t_2 are timepoints before sealing and before opening of the sampling box, respectively; T_1 and T_2 are the air temperature before sealing and before opening of the sampling box, respectively, (°C); C_1 and C_2 are volume fraction of greenhouse gas before sealing and before opening of the sampling box, respectively; M_0 is the molar mass of N_2O, ($g \cdot mol^{-1}$) and 22.4 is the molar volume of N_2O at 101.325 kPa, 273 K, ($L \cdot mol^{-1}$).

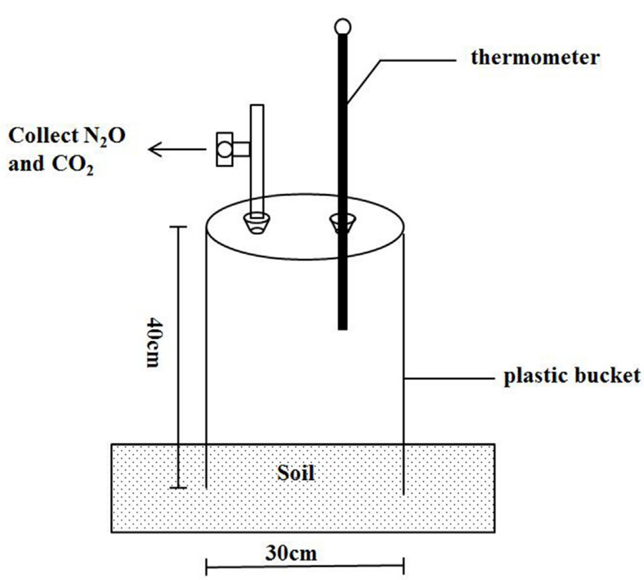

Fig. 3. The sketch of collection of N_2O and CO_2.

2.8. Combined global warming potential of CO_2 and N_2O

At 20 y, the global warming potential (GWP) per unit mass of N_2O is 275 times that of CO_2. At 100 y, the GWP per unit mass of N_2O is 296 times that of CO_2. At 500 y, the GWP per unit mass of N_2O is 156 times that of CO_2. If the GWP of 1 g m^{-2} CO_2 flux is 1, the combined GWP of CO_2 and N_2O emitted by various treatments at 20 y could be obtained (GWP = cumulative CO_2 emission × 1 + cumulative N_2O emissions × 275). Similarly, the GWP at 100 y and 500 y for various treatments could be calculated (IPCC, 2001).

2.9. Statistical analysis

Each measurement was repeated three or five times, and the mean values of each parameter were calculated. DPS software was used to collect data, and analysis of differences was processed using the Duncan's new multiple range method. The differences among means and correlation coefficients were considered significant when $p < 0.05$.

3. Results and discussion

3.1. Effects of BCRF on spatiotemporal changes in soil nitrogen

Ammoniacal nitrogen and nitrate nitrogen in soil were the major sources of nitrogen loss. Although it is essential that a suitable amount of available nitrogen is present, excessive available nitrogen will inevitably increase nitrogen loss (Zhu, 2000). Currently, excessive fertilizer application often occurs when nitrogen fertilizers are used in orchards, which does not increase soil inorganic nitrogen (Meheriuk et al., 1995). From Fig. 4, we can see that on Day 10 after fertilizer application, under the BCRF treatment, total N content in the 0–2 cm soil sample showed significant increase, but the increase in the 2–4 cm and 4–6 cm soil samples was smaller. On Day 50 after fertilizer application, under the BCRF treatment, the total N content of the 0–2 cm soil sample continued to increase while the 2–4 cm and 4–6 cm soil samples showed a significant increase in total N content. On Day 90 after fertilizer application, under BCRF treatment, the total N content of the 0–2 cm soil sample continued to increase while the total N content of 2–4 cm and 4–6 cm soil samples was maintained at high levels. Compared with BCRF, soil total N content increases more rapidly and decreases more rapidly with regular fertilizers. In contrast, total N content stably increases during the entire experiment with BCRF and did not show any signs of decrease on Day 90 of the experiment. These observations are indirectly consistent with other findings described in the literature (Zheng et al., 2016) and confirm that the coating material can effectively prevent the contact of urea particles in the bag with soil moisture and slow down the dissolution rate of urea in the bag and stable nitrogen content in soil.

In Fig. 5, it can be observed that on Day 10 the total N content in the vertical 0–2 and 2–4 cm soil layers increases under the BCRF treatment, but the increase was lower than that of the regular fertilizers. On Day 50 of fertilizer application, total N content in the vertical soil layers at the depth of 0–12 cm under the BCRF treatment continued to increase and was higher than that of the Control. On Day 90 of fertilizer application, the total N content of different vertical soil layers at the depth range of 0–12 cm under the BCRF fertilizer treatment was maintained at high levels, which was higher than that of ECF. Compared with regular fertilizers, BCRF caused N content to slowly increase vertically from the fertilizer

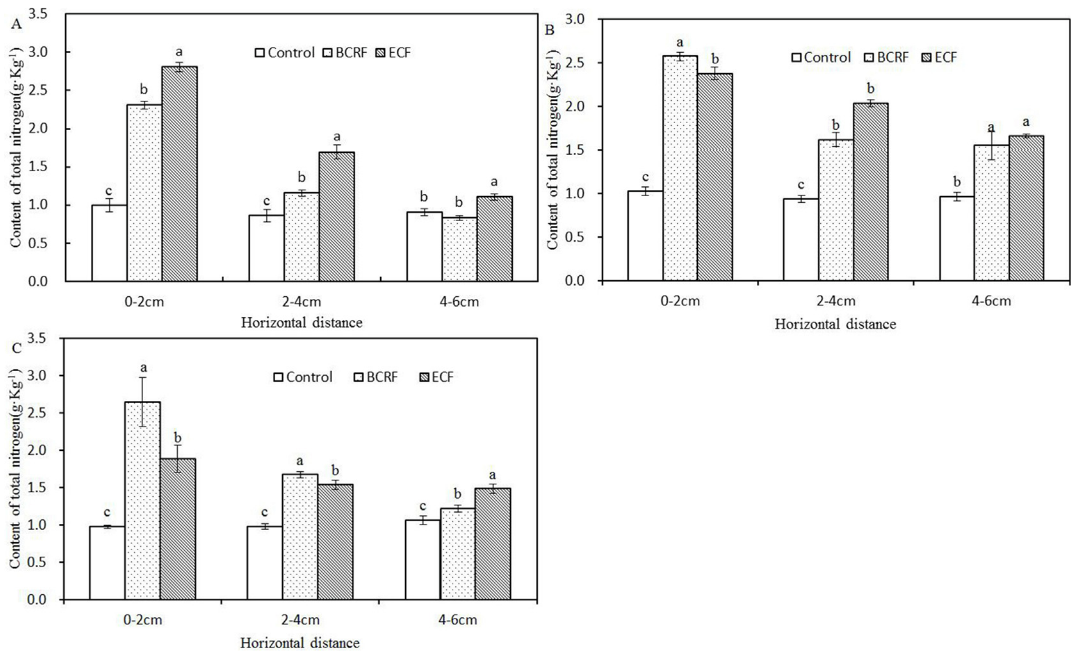

Fig. 4. Effects of BCRF on horizontal changes in soil total nitrogen
BCRF: bag-controlled release fertilizer (95
g/bag) with common composite mixed fertilizer. Urea, diammonium hydrogen phosphate, and potassium sulfate in a ratio of 41:14:40 ($N:P_2O_5:K_2O$). ECF: equal amount of common composite fertilizer mixed in the same ratio of $N:P_2O_5:K_2O$ as the BCRF. Control: no fertilizer application. Each point represents the mean ± standard error (n = 3). A: 10 days after treatment; B: 50 days after treatment; C: 90 days after treatment.

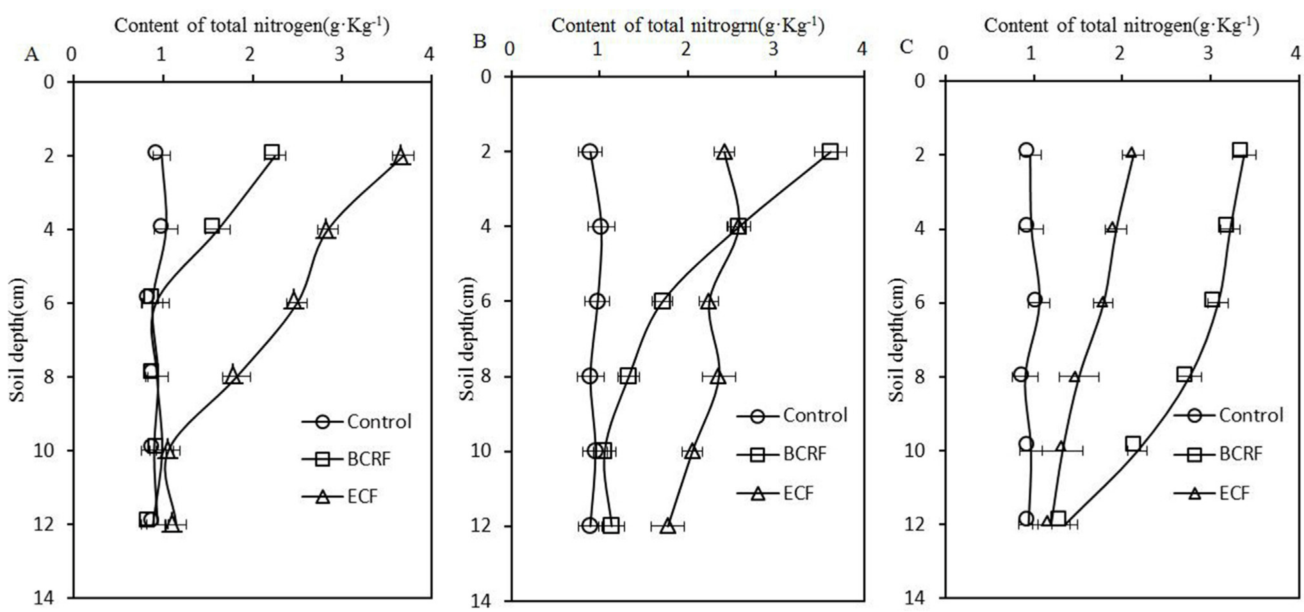

Fig. 5. Effects of BCRF on vertical changes in soil total nitrogen
BCRF: bag-controlled release fertilizer (95
g/bag) with common composite mixed fertilizer. Urea, diammonium hydrogen phosphate, and potassium sulfate in a ratio of 41:14:40 ($N:P_2O_5:K_2O$). ECF: equal amount of common composite fertilizer mixed in the same ratio of $N:P_2O_5:K_2O$ as the BCRF. Control: no fertilizer application. Each point represents the mean ± standard error (n = 3). A: 10 days after treatment; B: 50 days after treatment; C: 90 days after treatment.

application point and remain at relatively high levels.

In Fig. 6, it is evident that on Day 10, the nitrate N content in the horizontal 0–2 cm soil sample increased under the BCRF treatment but no significant increase in nitrate N content was observed in the 2–6 cm soil samples. On Day 50 after fertilizer application, under the BCRF application, the nitrate N content of the 0–6 cm soil samples continued to increase which was higher than that of ECF. On Day 90 after fertilizer treatment, under the BCRF application, the nitrate N content of the 0–6 cm soil samples of continued to remain at relatively high levels.

In Fig. 7, we can see that on Day 10 of fertilizer application, the nitrate N content in the vertical soil layers at the depth of 0–8 cm

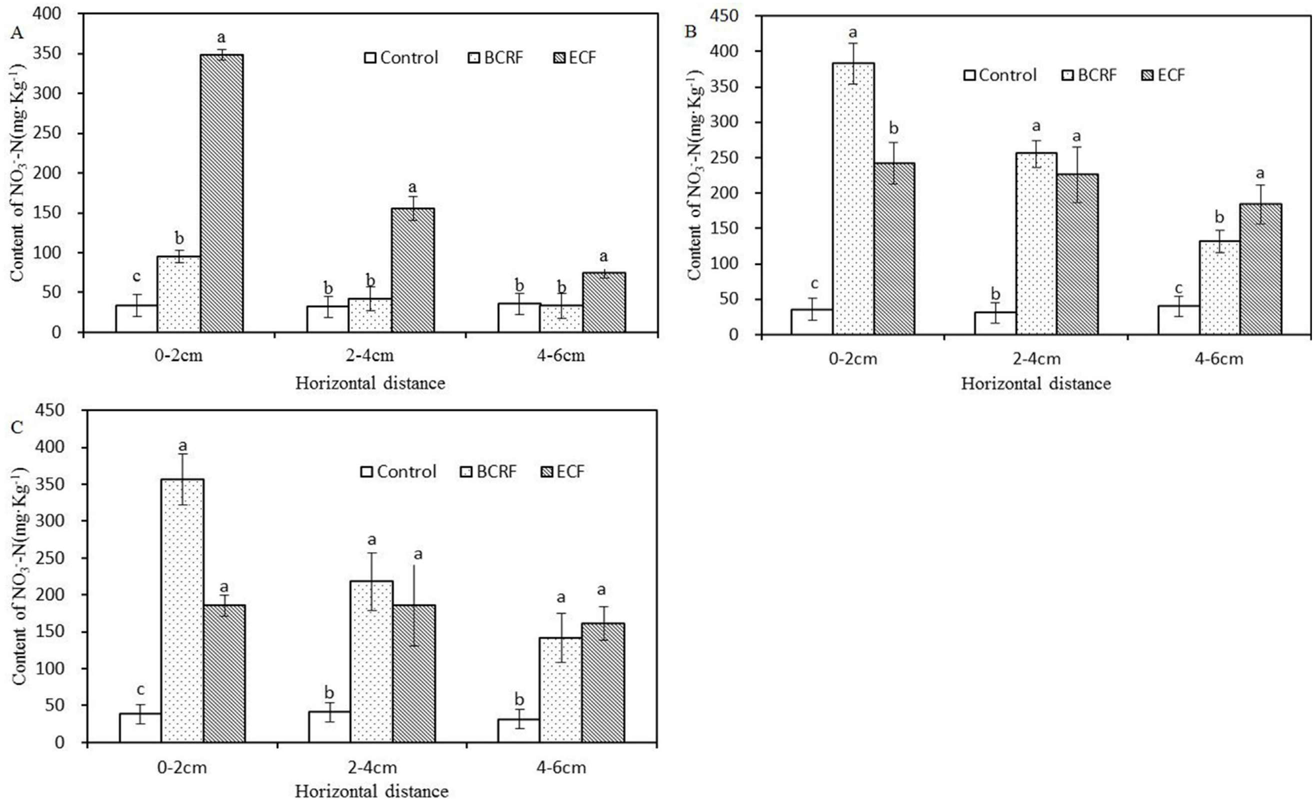

Fig. 6. Effects of BCRF on horizontal changes in soil nitrate nitrogen
BCRF: bag-controlled release fertilizer (95
g/bag) with common composite mixed fertilizer. Urea, diammonium hydrogen phosphate, and potassium sulfate in a ratio of 41:14:40 ($N:P_2O_5:K_2O$). ECF: equal amount of common composite fertilizer mixed in the same ratio of $N:P_2O_5:K_2O$ as the BCRF. Control: no fertilizer application. Each point represents the mean ± standard error (n = 3). A: 10 days after treatment; B: 50 days after treatment; C: 90 days after treatment.

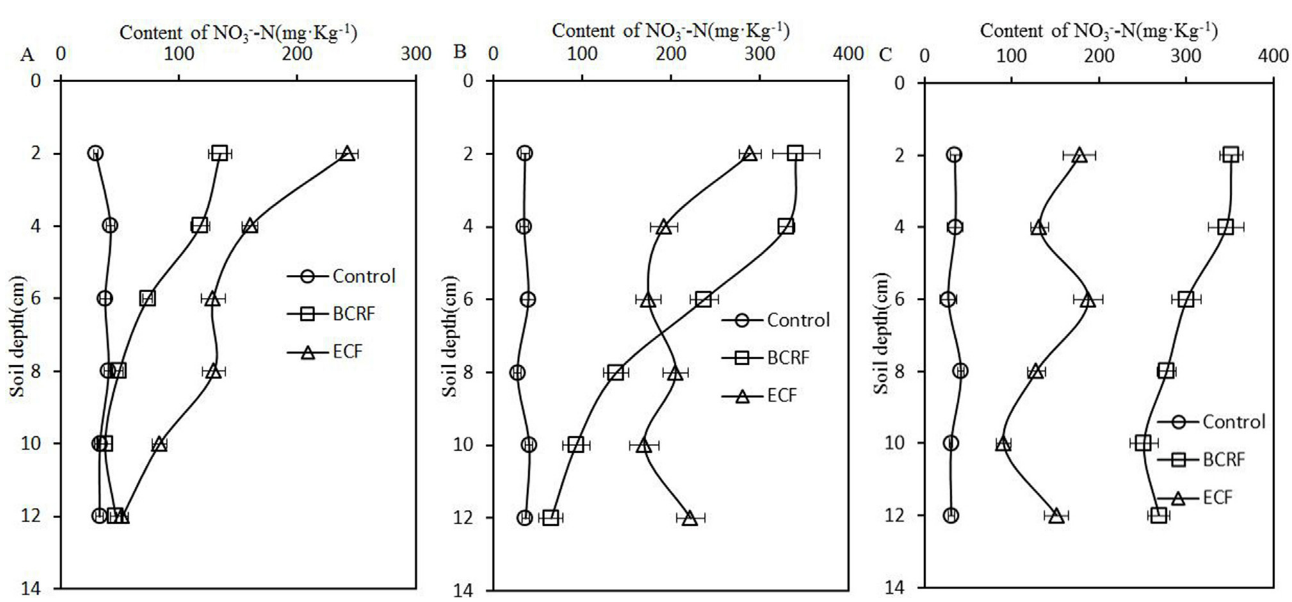

Fig. 7. Effects of BCRF on vertical changes in soil nitrate nitrogen
BCRF: bag-controlled release fertilizer (95
g/bag) with common composite mixed fertilizer. Urea, diammonium hydrogen phosphate, and potassium sulfate in a ratio of 41:14:40 ($N:P_2O_5:K_2O$). ECF: equal amount of common composite fertilizer mixed in the same ratio of $N:P_2O_5:K_2O$ as the BCRF. Control: no fertilizer application. Each point represents the mean ± standard error (n = 3). A: 10 days after treatment; B: 50 days after treatment; C: 90 days after treatment.

increased under the BCRF treatment, which was higher than under the Control but lower than under ECF. On Day 50 of fertilizer application, the nitrate N content in the vertical soil layers at the depth of 0–12 cm increased under the BCRF treatment, of which the nitrate N content of the soil layers at the depth of 0–6 cm rapidly increased and were higher than that of the ECF. On Day 90 of fertilizer application, the nitrate N content of the vertical soil layers at the depth of 0–12 cm under the BCRF treatment continued to increase and was higher than under ECF.

In Fig. 8, we can see that on Day 10 of fertilizer application, ammoniacal N content in the horizontal 0–2 cm soil sample increased under the BCRF treatment, but the ammoniacal N content of the soil samples of 2–6 cm did not show any significant increase when compared with the Control. On Day 50 after fertilizer application, under the BCRF application, the ammoniacal N content of the 0–4 cm horizontal soil samples showed significant increases. On Day 90 after fertilizer application, under the BCRF application, the ammoniacal N content of the 0–6 cm horizontal soil samples started to decrease.

In Fig. 9, we can see that on Day 10 after fertilizer application, under the BCRF treatment, the ammoniacal N content in the vertical soil layers at the depth of 0–4 cm increased, but ammoniacal N content in the soil layers at the depth of 4–12 cm did not significantly increase when compared with the Control. On Day 50 of fertilizer application, under the BCRF treatment, the ammoniacal N content of the vertical soil layers at the depth of 0–6 cm increased, of which the ammoniacal N content of the 0–2 cm soil layer was higher than that of the ECF, but the ammoniacal N content of the soil layers at the depth of 8–12 cm did not show any significant increase when compared with the Control. On Day 90 after fertilizer application under the BCRF application, the ammoniacal N content of the various vertical soil layers at the depth of 2–12 cm increased, but the ammoniacal N content of the different soil layers was higher than that of both the Control and ECF. However, our study of the effects of BCRF on spatiotemporal changes in soil nitrogen was carried out in soil conditions without peach trees. Since the roots of peach trees can absorb the nutrients in the soil, the effects of BCRF on spatiotemporal changes in the soil nitrogen under peach trees remains to be further studied, especially for ammoniacal N and nitrate N.

3.2. Effects of BCRF on the level of nitrogen leaching and salt-based ion leaching

After application of ordinary chemical fertilizers by spreading, soil available nitrogen concentration will rapidly increase in a short period of time. During this period, rainfall or irrigation will result in nitrogen loss. Therefore, the method of applying fertilizer by spreading results in large fluctuations in available nitrogen concentrations (Weinbaum et al., 1992). Large amounts of nitrogen undergo nitrification and denitrification, which then enter groundwater or are volatilized, causing serious environmental problems. From Fig. 10A, we can see that among the different leachates, comparison of the different treatments showed that the leaching loss of nitrate N when the leachate volume is equivalent to 0.4 and 0.8 times the soil void volume follows the pattern of ECF > BCRF > Control, ie., leaching loss under regular fertilizer treatment is significantly higher than that of the BCRF treatment and Control. The leachate nitrate N content under regular fertilizer treatment is slightly higher than other treatments which are in

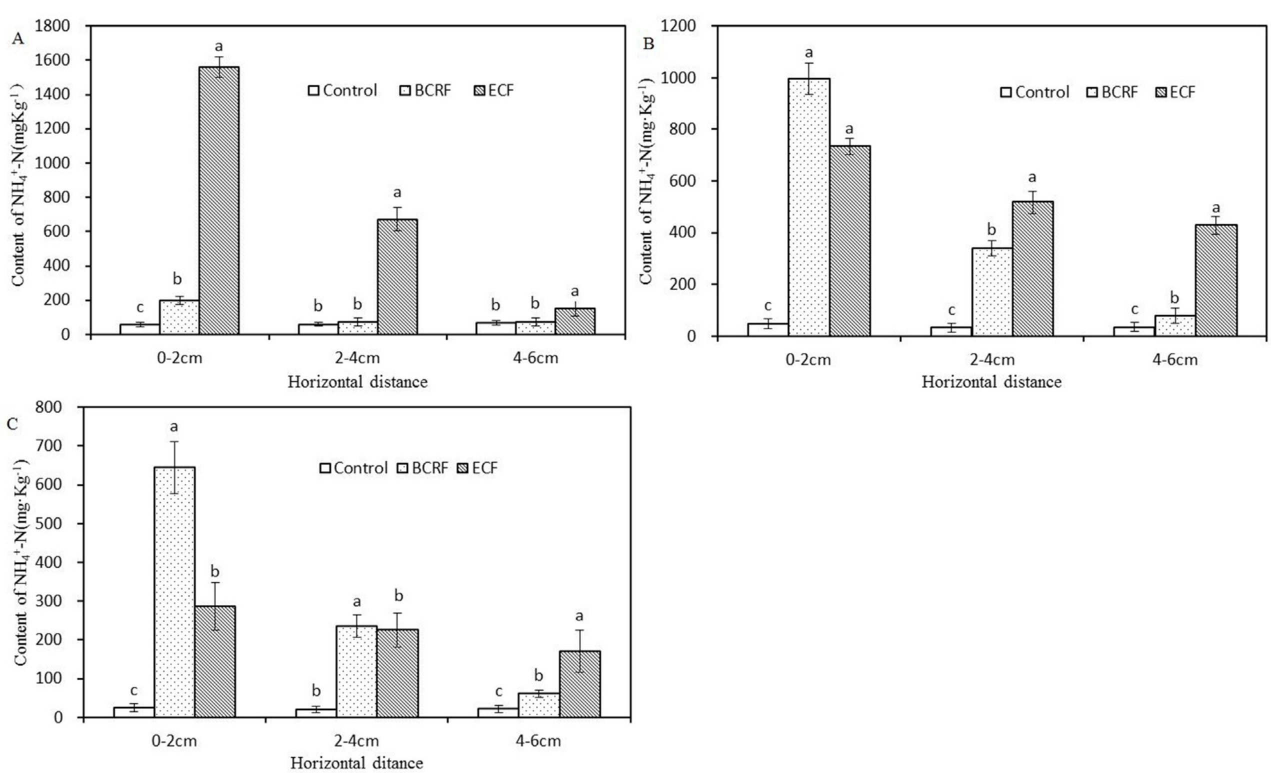

Fig. 8. Effects of BCRF on horizontal changes in soil ammoniacal nitrogen
BCRF: bag-controlled release fertilizer (95
g/bag) with common composite mixed fertilizer. Urea, diammonium hydrogen phosphate, and potassium sulfate in a ratio of 41:14:40 (N:P_2O_5:K_2O). ECF: equal amount of common composite fertilizer mixed in the same ratio of N:P_2O_5:K_2O as the BCRF. Control: no fertilizer application. Each point represents the mean ± standard error (n = 3). A: 10 days after treatment; B: 50 days after treatment; C: 90 days after treatment.

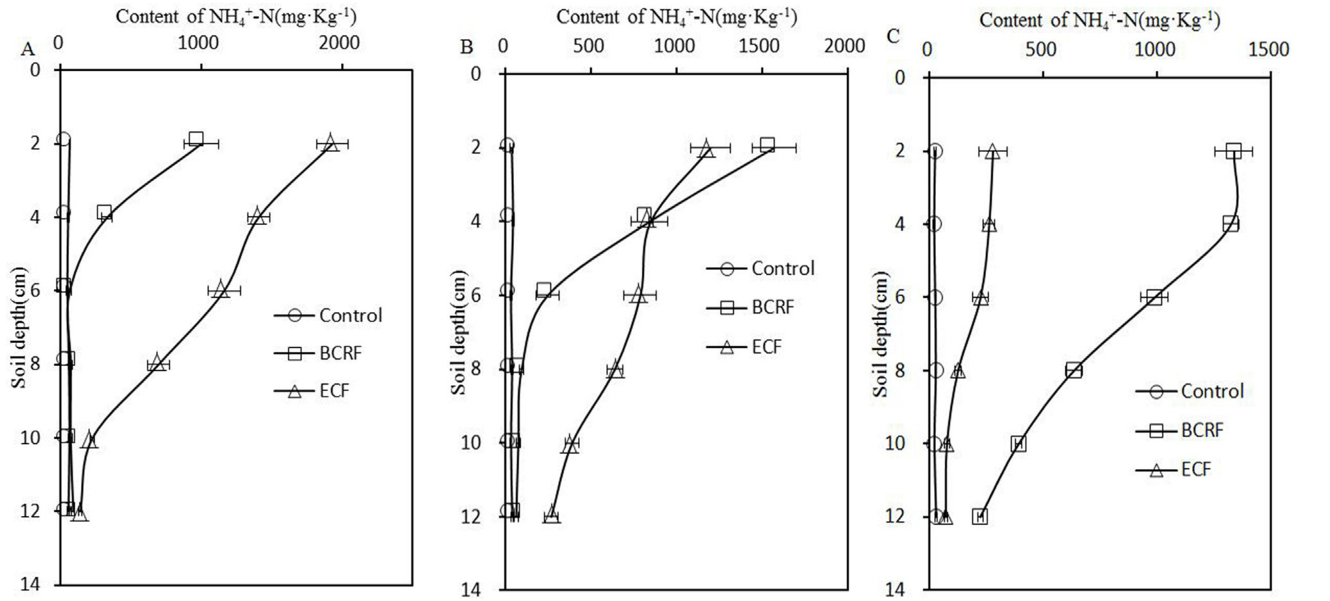

Fig. 9. Effects of BCRF on vertical changes in soil ammoniacal nitrogen
BCRF: bag-controlled release fertilizer (95
g/bag) with common composite mixed fertilizer. Urea, diammonium hydrogen phosphate, and potassium sulfate in a ratio of 41:14:40 ($N:P_2O_5:K_2O$). ECF: equal amount of common composite fertilizer mixed in the same ratio of $N:P_2O_5:K_2O$ as the BCRF. Control: no fertilizer application. Each point represents the mean ± standard error (n = 3). A: 10 days after treatment; B: 50 days after treatment; C: 90 days after treatment.

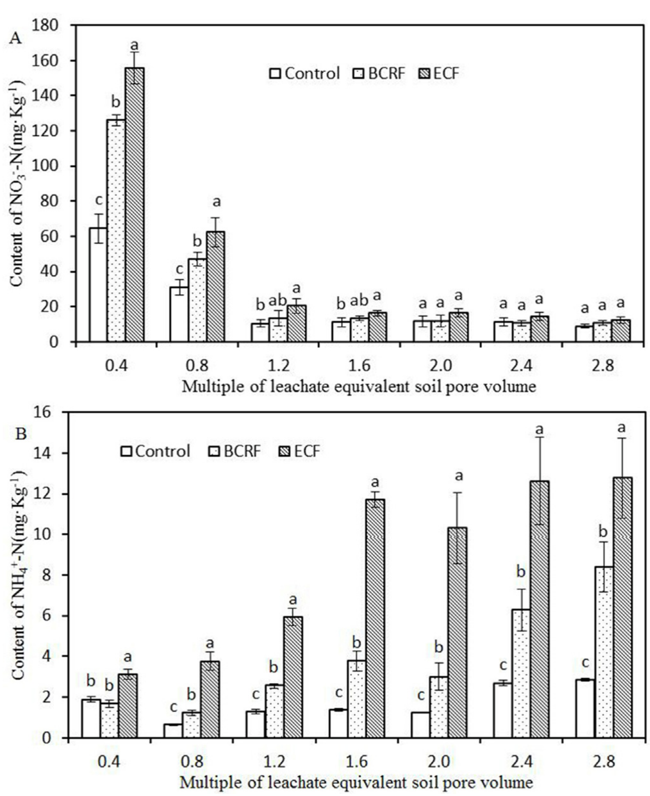

Fig. 10. Effects of BCRF on the level of nitrate nitrogen and ammoniacal nitrogen in leachates
BCRF: bag-controlled release fertilizer (95
g/bag) with common composite mixed fertilizer. Urea, diammonium hydrogen phosphate, and potassium sulfate in a ratio of 41:14:40 ($N:P_2O_5:K_2O$). ECF: equal amount of common composite fertilizer mixed in the same ratio of $N:P_2O_5:K_2O$ as the BCRF. Control: no fertilizer application. Each point represents the mean ± standard error (n = 3).

agreement with Liu et al. (2011) and other researchers.

Nitrogen fertilizer is partially absorbed by the crop in the soil and leaches with precipitation and irrigation water (Knight et al., 2007). The reason why nitrate N reaches relatively high levels at the early stages of leaching is because soil colloids are negatively charged and do not adsorb NO_3^-. Therefore, nitrate ions in soil will be rapidly lost with leaching. The sources of nitrate lost in leaching were from the soil and fertilizers. After regular fertilizers were applied to soil, they rapidly dissolve, and some N in the fertilizer is converted to nitrate N. Because the nutrients released by regular fertilizers were far higher than those released by BCRF, the amount of nitrate N lost by leaching is also higher.

Fig. 10B shows the changes in ammoniacal N lost by leaching. Overall, the leaching loss of ammoniacal N shows a gradually increasing trend. N can leave the soil-plant system through various conversion and migration processes, thereby causing economic losses due to N fertilizers and a risk of adverse effects on the environment, which do not benefit clean production. Therefore, adopting various techniques and measures to reduce N loss is one of the core tasks in agricultural management. Ammoniacal N exists in the NH_4^+ state in soil, is easily adsorbed by soil colloids, and is not easily lost by leaching. After application of regular fertilizers on soil, N is continuously converted to large amounts of ammoniacal N. This causes some ammoniacal N to be unable to adsorb to soil and be lost by leaching. In contrast, using BCRF can slowly release N, and consequently, soil ammoniacal N slowly increases. Most ammoniacal N is adsorbed, which decreases the loss of ammoniacal N by leaching.

Leaching is one of the major routes of N loss, and most N is lost in the form of nitrate N. In soil, it is difficult for nitrate N to be adsorbed by soil colloids. Subtraction of the Control from N loss under different fertilizer applications gives the loss caused by application of N fertilizers. From Fig. 11, we can see that the N loss rate under the BCRF treatment is significantly lower than ECF. Therefore, BCRF significantly decreases N loss caused by leaching.

As shown in Fig. 12, BCRF significantly reduced salt-based ion

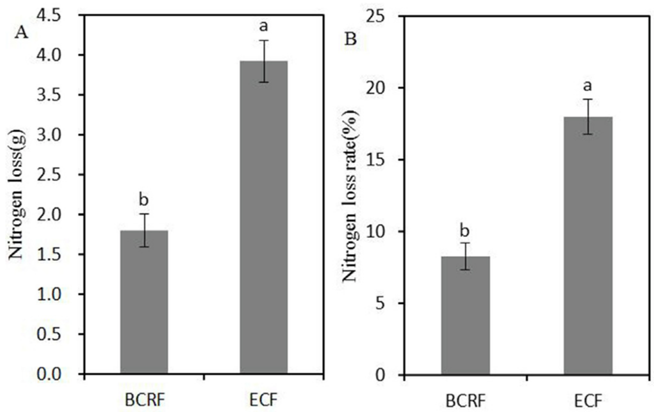

Fig. 11. Effects of BCRF on nitrogen loss by leaching.
BCRF: bag-controlled release fertilizer (95
g/bag) with common composite mixed fertilizer. Urea, diammonium hydrogen phosphate, and potassium sulfate in a ratio of 41:14:40 ($N:P_2O_5:K_2O$). ECF: equal amount of common composite fertilizer mixed in the same ratio of $N:P_2O_5:K_2O$ as the BCRF. Control: no fertilizer application. Each point represents the mean ± standard error (n = 3). Different lowercase letters indicate a significant difference between treatments (P<5%).

leaching. After application of regular fertilizers in soil, the fertilizer undergoes rapid dissolution and conversion, generating large amounts of NH_4^+ and K^+, which were monovalent cations. This creates a transient high concentration "micro-region" in the soil surrounding the fertilizer application point, causing salt ions around the micro-region to be replaced by monovalent ions from the fertilizer, which are lost when water moves downwards. BCRF releases nutrients slowly and will not produce such high concentration micro-regions. Therefore, the amount of salt ions lost by leaching is low, which is indirectly consistent with other findings described in the literature (Chen et al., 2005) and confirms that the release rate of controlled release fertilizer is relatively slow, so that the nutrient release rate of the fertilizer is closer to the nutrient requirement of the crop, which is beneficial to the absorption of the crop and reduce the leaching of nitrate nitrogen.

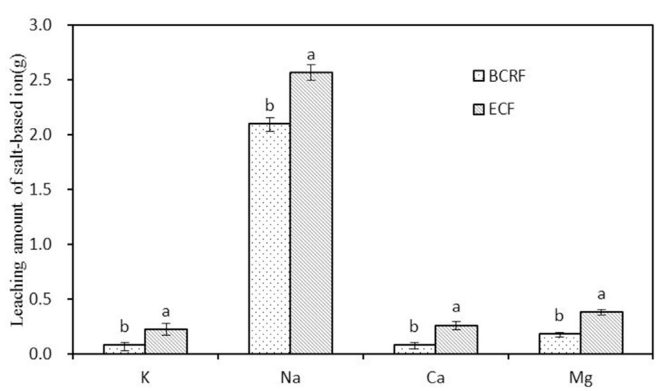

Fig. 12. Effect of BCRF on salt-based ion leaching
BCRF: bag-controlled release fertilizer (95
g/bag) with common composite mixed fertilizer. Urea, diammonium hydrogen phosphate, and potassium sulfate in a ratio of 41:14:40 ($N:P_2O_5:K_2O$). ECF: equal amount of common composite fertilizer mixed in the same ratio of $N:P_2O_5:K_2O$ as the BCRF. Control: no fertilizer application. Each point represents the mean ± standard error (n = 3). Different lowercase letters indicate a significant difference between treatments (P<5%).

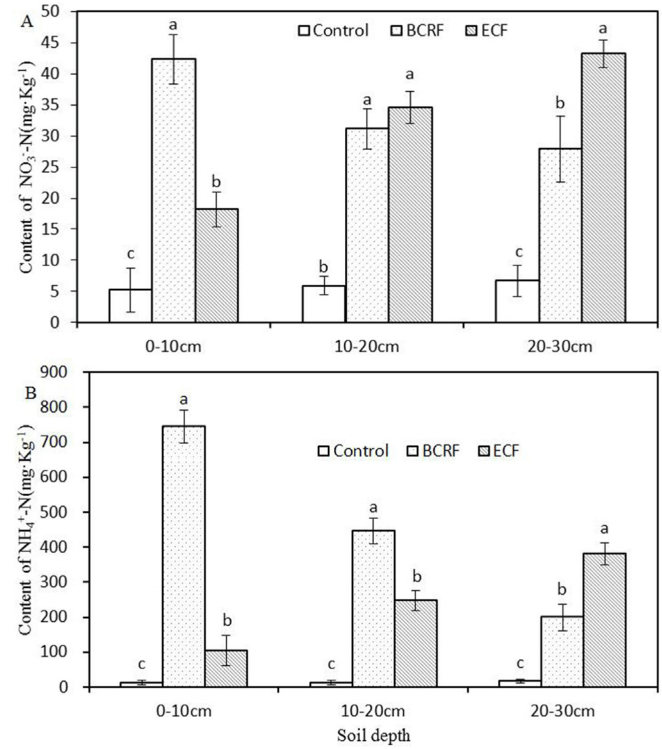

Fig. 13. Effect of BCRF on soil nitrogen content after leaching
BCRF: bag-controlled release fertilizer (95
g/bag) with common composite mixed fertilizer. Urea, diammonium hydrogen phosphate, and potassium sulfate in a ratio of 41:14:40 ($N:P_2O_5:K_2O$). ECF: equal amount of common composite fertilizer mixed in the same ratio of $N:P_2O_5:K_2O$ as the BCRF. Control: no fertilizer application. Each point represents the mean ± standard error (n = 3). Different lowercase letters indicate a significant difference between treatments (P<5%).

3.3. Effect of BCRF on soil N content after leaching

In Fig. 13A, we can see that after leaching, the nitrate N content of the 0–30 soil layer under the BCRF treatment was significantly higher than that of the regular fertilizer treatments. Nitrate N in soil originates from two sources, namely conversion from NH_4^+-N in soil and the leaching of NO_3^--N in the upper soil layers. Under the regular fertilizer treatment, as the NH_4^+-N content in upper soil layers was lower than BCRF treatment. The amount converted to NO_3^--N is also lower. In the lower layers, the NH_4^+-N content is higher than in the upper layers, and there is accumulation of NO_3^--N that is leached from the upper layers. Therefore, the nitrate N content is lower in the upper layers and higher in the lower layers.

We can see from Fig. 13B that after the completion of the leaching process, the ammoniacal N content of the 0–30 soil layer under the BCRF treatment was significantly higher than that of the regular fertilizer treatments. Although NH_4^+-N can be adsorbed by soil colloid, as leaching intensity increases, NH_4^+-N at the upper layers will gradually leach and accumulate at deeper soil layers while some NH_4^+-N was converted to NO_3^--N and lost. However, although NH_4^+-N in the upper layers of the BCRF samples were also lost, BCRF can continuously release N and the NH_4^+-N content of the upper layers was higher than that of the lower layers.

Based on the aforementioned analysis, BCRF can maintain N at higher levels at the fertilizer application point, preventing the loss of N in deeper soil layers and reducing the potential threat of groundwater pollution.

3.4. BCRF decreases NH_3 volatilization and greenhouse gas emission

Ordinary urea quickly combines with water in the soil to form a high ammonia pressure, resulting in a large amount of ammonia volatilized soon after being applied to the soil (Mandal et al., 2016). BCRF can significantly decrease ammonia volatilization and greenhouse gas emissions (Fig. 14A). The ammonia volatilization rates of BCRF and ordinary fertilizer were significantly different. Volatilization peaks were simultaneously achieved on Day 5 after fertilizer application with two different application levels (ECF) of ordinary fertilizers. Subsequently, volatilization rapidly decreased and gradually reached a plateau. No volatilization was detected on Day 72. Volatilization reached its peak on Day 15 for BCRF. Subsequently, volatilization gradually decreased, and no volatilization was detected on Day 125. The volatilization rate peak for ECF was 7.09 times that of BCRF, and the volatilization rate peak for ordinary fertilizer was significantly greater than that of BCRF. Compared with ordinary fertilizers, the variation curve of BCRF was gentler, and peak appearance was delayed by 10 days.

After ordinary fertilizers were applied to the soil, the nylon mesh cannot effectively prevent fertilizer and soil from coming in contact with each other. Nitrogen was rapidly dissolved and hydrolyzed to generate large amounts of nitrogen. As nitrogen accumulates, soil nitrogen concentration increases, and NH_3 diffusion was strengthened. This causes NH_3 volatilization and loss within a short period of time. In contrast to ordinary fertilizers, BCRF can effectively delay nitrogen dissolution and release. Soil nitrogen concentrations were maintained at low levels as nitrogen was slowly released and no large volatilization peak occurred.

After urea is applied to soil, it is rapidly hydrolyzed to ammoniacal nitrogen under the action or urease. As nutrients are released faster under ordinary fertilizer treatment, it results in higher soil ammoniacal nitrogen content in the early stages after fertilizer application. However, this phenomenon provides sufficient substrate for nitrification, so that soil nitrification is active, which further provides large amounts of denitrification and promotes denitrification (Bandibas et al., 1994). Therefore, NH_3 volatilization rapidly occurs at the early stages of fertilizer application, and N_2O emissions reaches a peak. However, nitrogen in the BCRF can only be slowly released through the micro holes. This causes soil nitrogen to slowly increase and be maintained at a certain concentration, weakening the peak values for NH_3 volatilization and N_2O emissions and delaying them for 10–15 days.

From Fig. 14B, we can see that a significant emission peak was present in all treatments. Compared with ordinary fertilizer treatment, BCRF can significantly weaken and delay the N_2O emission peak. After the ECF ordinary fertilizer was applied to soil, a N_2O emission peak appeared on Day 3. The difference between the BCRF treatment and the Control treatment during the first four days of application was not great, and N_2O emissions were only significantly increased from Day 5 onwards, reaching a peak on Day 18. The emission peak was delayed by 15 days. There were significant differences in N_2O emission peak values between the different treatments, with the peak value of ECF being 5.6 times that of BCRF. Therefore, BCRF treatment significantly weakened the N_2O emission peak. It can be seen that controlled-release fertilizer can significantly reduce the daily emission of N_2O.

The variation trend of the daily CO_2 emission curve was similar to that of N_2O (Fig. 14C). The ECF treatment reaches its peak rapidly on Day 3 after fertilizer application before rapidly decreasing, and was lower than the emission amount from BCRF on Day 11 onwards. The daily CO_2 emission flux of the BCRF treatment was maintained at a low level, and there was no significant emission peak. Compared with ordinary fertilizers, BCRFs significantly decreased NH_3 volatilization and cumulative N_2O emissions. The study by Sun et al. (2004) showed that coated controlled-release fertilizers decreased NH_3 volatilization by 12.3%–71.2% while the study by Du et al. (2011) showed that coated controlled-release fertilizers decreased cumulative N_2O emissions by 30.5%–89.3%. Therefore, the effects of BCRF in reducing NH_3 volatilization and N_2O emissions were similar to coated controlled-release fertilizers.

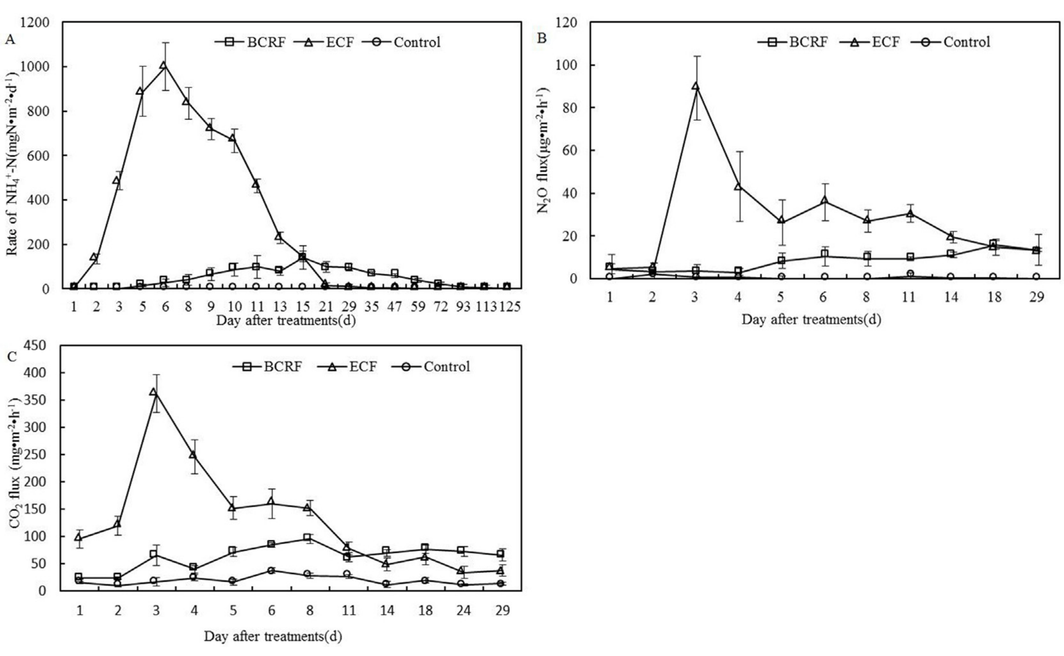

Fig. 14. Rate of NH_3 volatilization, characteristics of daily N_2O and daily CO_2 emissions from soil of different fertilization treatments.
BCRF: bag-controlled release fertilizer (95
g/bag) with common composite mixed fertilizer. Urea, diammonium hydrogen phosphate, and potassium sulfate in a ratio of 41:14:40 ($N:P_2O_5:K_2O$). ECF: equal amount of common composite fertilizer mixed in the same ratio of $N:P_2O_5:K_2O$ as the BCRF. Control: no fertilizer application. Each point represents the mean ± standard error (n = 3).

Table 2
NH_3, N_2O and CO_2 accumulation of different treatments.

Treatments	Cumulative amount of NH_3 volatilization (in N) ($g \cdot m^{-2}$)	Cumulative emissions of N2O (in N) (g·m-2)	Cumulative emissions of CO_2($g \cdot m^{-2}$)
ECF	7.720a	0.0228a	62.57a
BCRF	3.692b	0.0115bc	47.87b
Control	0.001d	0.00071d	12.74d

BCRF: bag-controlled release fertilizer(95 g/bag) with ordinary composite mixed fertilizer. Urea, diammonium hydrogen phosphate, and potassium sulfate in a ratio of 41:14:40 ($N:P_2O_5:K_2O$). ECF: equal amount of common composite fertilizer mixed in the same ratio of $N:P_2O_5:K_2O$ as the BCRF. Control: no fertilizer application. Different lowercase letters indicate a significant difference between treatments (P<5%).

Table 3
The rate of nitrogen loss under different treatments.

Treatment	Loss rate of NH_3 volatilization (%)	Loss rate of N_2O emissions (%)	Total loss rate of (NH_3+N_2O) (%)
ECF	17.69a	0.0523 ab	17.74a
BCRF	8.46b	0.0263c	8.50b

BCRF: bag-controlled release fertilizer(95 g/bag) with ordinary composite mixed fertilizer. Urea, diammonium hydrogen phosphate, and potassium sulfate in a ratio of 41:14:40 ($N:P_2O_5:K_2O$). ECF: equal amount of common composite fertilizer mixed in the same ratio of $N:P_2O_5:K_2O$ as the BCRF. Different lowercase letters indicate a significant difference between treatments (P<5%).

3.5. BCRF reduces cumulative NH_3 volatilization and cumulative N_2O emissions from soil

BCRFs decrease cumulative NH_3 volatilization and cumulative N_2O emissions from soil (Tables 2 and 3) which is in agreement with Wilson et al. (2010) and Nash et al. (2015) study on polymer-coated urea. BCRF can significantly reduce NH_3 volatilization and loss. For instance, cumulative emission under the BCRF treatment was reduced by 52.18% compared with ECF. NH_3 volatilization is an important route for nitrogen loss. Results showed that the proportion of nitrogen loss due to NH_3 volatilization in total applied nitrogen was significantly higher in the ECF treatment than the BCRF treatment, and BCRF reduced nitrogen loss by 55.86%. BCRF can reduce N_2O emissions by 49.56%. The cumulative N_2O emitted under the BCRF and ECF treatments accounted for 0.026% and 0.0523% of the nitrogen fertilizers applied, respectively. The cumulative emission loss rate of N_2O from the BCRF treatment was 0.5 times that of the ECF treatment. It can be seen that BCRF application can significantly reduce the loss rate of N_2O by emissions from nitrogen fertilizers which is in agreement with Cheng et al. (2004) and other researchers. Thus the effect of BCRF on reducing NH_3 volatilization and N_2O emissions is similar to that of coated controlled release fertilizers.

Lin et al. (2008) carried out a survey in the Three Gorges Reservoir region and found that the N_2O emission flux and total emissions in orchards were only lower than vegetable fields and is the highest among the different utilization methods. The main reason for this is the high amount of fertilizers applied in orchards. The study by Peng et al. (2006) on Zhanhua winter jujubes found that there was no significant difference in yield at Year 3 between 7 bags/tree and 10 bags/tree when BCRF was used. Therefore, fertilizer application in orchards should be appropriately reduced according to soil and plant nutritional status to protect the ecological environment. This experiment studied the effects of BCRF on soil NH_3 volatilization as well as N_2O and CO_2 emissions from the soil with no peach trees. Whether it will further reduce NH_3 volatilization, and emissions of N_2O and CO_2 from the soil with the absorption effect of peach roots remains to be further verified.

3.6. BCRF reduces the combined greenhouse effects of CO_2 and N_2O

From Table 4, we can see that the global warming potential (GWP) per unit mass of N_2O was 275 times that of CO_2 at the 20-year scale. At the 100-year scale, the GWP per unit mass of N_2O was 296 times that of CO_2. At the 500-year scale, the GWP per unit mass of N_2O was 156 times that of CO_2. When compared with the mean values of ordinary fertilizer treatments, the mean GWP value of two BCRF treatments were decreased by 28.31%, 28.63%, and 27.72% at the 20-, 100-, and 500- year, respectively. This shows that BCRF decreases the greenhouse effects of CO_2 and N_2O at both short and long time scales and decreases combined GWP.

Table 4
The integrated Global Warming Potential (GWP) of CO_2 and N_2O of the different treatments.

Treatment	GWP		
	20-Year	100-Year	500-Year
ECF	68.85a	69.33a	66.13a
BCRF	51.02b	51.26b	49.65b
Control	12.93d	12.95d	12.85d

BCRF: bag-controlled release fertilizer(95 g/bag) with ordinary composite mixed fertilizer. Urea, diammonium hydrogen phosphate, and potassium sulfate in a ratio of 41:14:40 ($N:P_2O_5:K_2O$). ECF: equal amount of common composite fertilizer mixed in the same ratio of $N:P_2O_5:K_2O$ as the BCRF. Control: no fertilizer application. Different lower-case letters indicate a significant difference between treatments (P<5%).

3.7. BCRF can provide stable nutrient supply to soil

The soil available nitrogen concentration increases rapidly in a short period of time after application of ordinary chemical fertilizers, and during this time, rainfall or irrigation may cause nitrogen loss, so the effective nitrogen concentration fluctuates greatly after the application of ordinary chemical fertilizers (Weinbaum et al., 1992). Under different fertilizer application methods, there were differences in the dynamic changes of available nitrogen, available phosphorus, and available potassium in soil. The soil nutrients of peach orchards where BCRF was applied were maintained at relatively stable levels for many continuous years. Therefore, BCRF can provide a stable nutrient supply for the growth and development of peach trees (Fig. 15), which is in agreement with Yan et al. (2004). Results showed that annual dynamic changes were similar when soil samples were collected at mid-April, July, and October every year after fertilizer application. Fixed point experiments in which

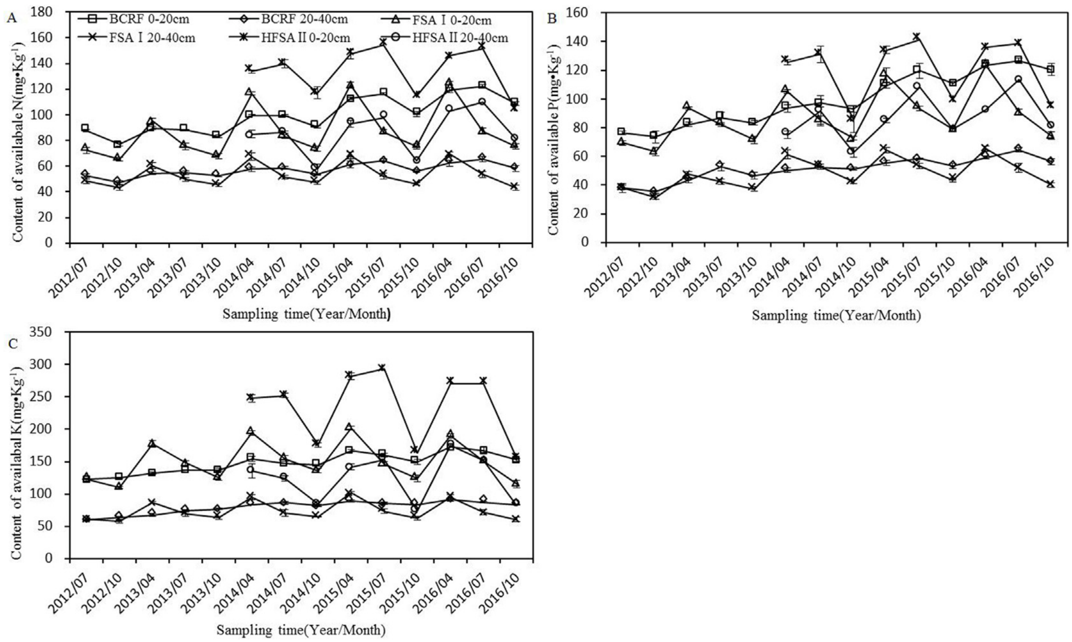

Fig. 15. The effect of BCRF on soil available nutrients in peach orchard.
BCRF: bag-controlled release fertilizer (95
g/bag) with common composite mixed fertilizer. Urea, diammonium hydrogen phosphate, and potassium sulfate in a ratio of 41:14:40 ($N:P_2O_5:K_2O$). FSA I: equal amount ditch application once: equal amount of common composite fertilizer mixed in the same ratio of $N:P_2O_5:K_2O$ as the BCRF. HFSA II: high-dose double ditch application twice with double amount of common composite fertilizer mixed in the same ratio of $N:P_2O_5:K_2O$ as the BCRF. Soil depths were 0–20 cm and 20–40 cm. Each point represents the mean ± standard error (n = 3).

BCRF was continuously applied for five years showed that soil available nutrient content was significantly increased in a short period of time after HFSA II but subsequent reduction in soil available nutrient content was faster. Compared with the FSA I treatment, soil available nutrient content under the BCRF treatment was more stable. This was particularly evident after ‘Ruipan 21’ enters the later stages of fruit development when soil nutrient levels under the FSA I treatment were lower while soil nutrient content under the BCRF treatment was still maintained at relatively high levels. The reason for this may be similar to nutrient release from coated fertilizers, which is actually the nutrient diffusion through the coating in coated fertilizers towards the outside (Du et al., 2005), and this may be similar to the release characteristics of nutrients from BCRF. The release rate of fertilizers has a direct relationship with soil nutrient concentration, i.e. as soil nutrients were absorbed and utilized by plants, fertilizers slowly release nutrients. This effectively decreases soil nutrient loss due to irrigation and rainwater and ensures stable soil nutrient content. Maintenance of relatively stable soil nutrient levels for many continuous years in peach orchards will provide stable nutrient supply for the growth and development of peach trees and ensure a balanced growth of the trees. During the experiment, we observed that many years of BCRF application resulted in healthy trees and stable tree structure. According to the plant steady state nutrient theory, if the nutrients were supplied based on the relative growth rate of plants, optimal growth can be achieved (Yan et al., 2004).

The coated controlled release fertilizer can adjust the nutrient release rate and release according to the demand of nutrients in different growth stages of crops, so that the nutrient release curve and the nutrient demand of the crop are synchronized (Geng et al., 2015; Gao et al., 2015). BCRF can only achieve the effect of slow release of nutrients. However, it could not accurately control the release of nutrients, and could not supply nutrients according to the demand for different nutrients at different growth stages of peach trees but were at least closer to its nutrient demands. In addition, due to the complexity of the peach orchard system, different tree ages, site conditions, and yield levels may affect the fertilization effect. Therefore, the optimization of BCRF application technology still requires more research.

3.8. BCRF can promote development of fine roots to form a dense root system in peach trees

From Fig. 16A, we can see that the horizontal distribution of the root system of peach trees reached 140, 160, and less than 100 cm under FSA I, HFSA II, and BCRF treatments, respectively. In addition, 74.41% of fine roots ($d \leq 2$ mm) under the BCRF treatment were within the 20–80 cm range. This shows that the root system distribution of spreading fertilizer application was not concentrated. From Fig. 16B, we can see that the proportion of fine roots was the highest after the BCRF treatment, accounting for 83.59% of the total root system length. The proportion of fine roots after the FSA I treatment was lower, accounting for 75.19% of the total root system length. However, the proportion of fine roots after the HFSA II treatment only accounted for 70.63% of the total root system length. This shows that BCRF application can promote the development of fine roots.

In this study, after the FSA I treatment, soil nutrient concentration was higher for a short period of time, but soil nutrient concentration was lower at the later stages, resulting in nutrient deficiency in the soil. In order to maintain the growth and development requirement of the tree, the root system extends outwards to absorb nutrients, thereby resulting in accelerated turnover, significant root extension, and further distribution range. After HFSA II application, large fluctuations in soil nutrient concentration occur, which affect the growth and development of the root system.

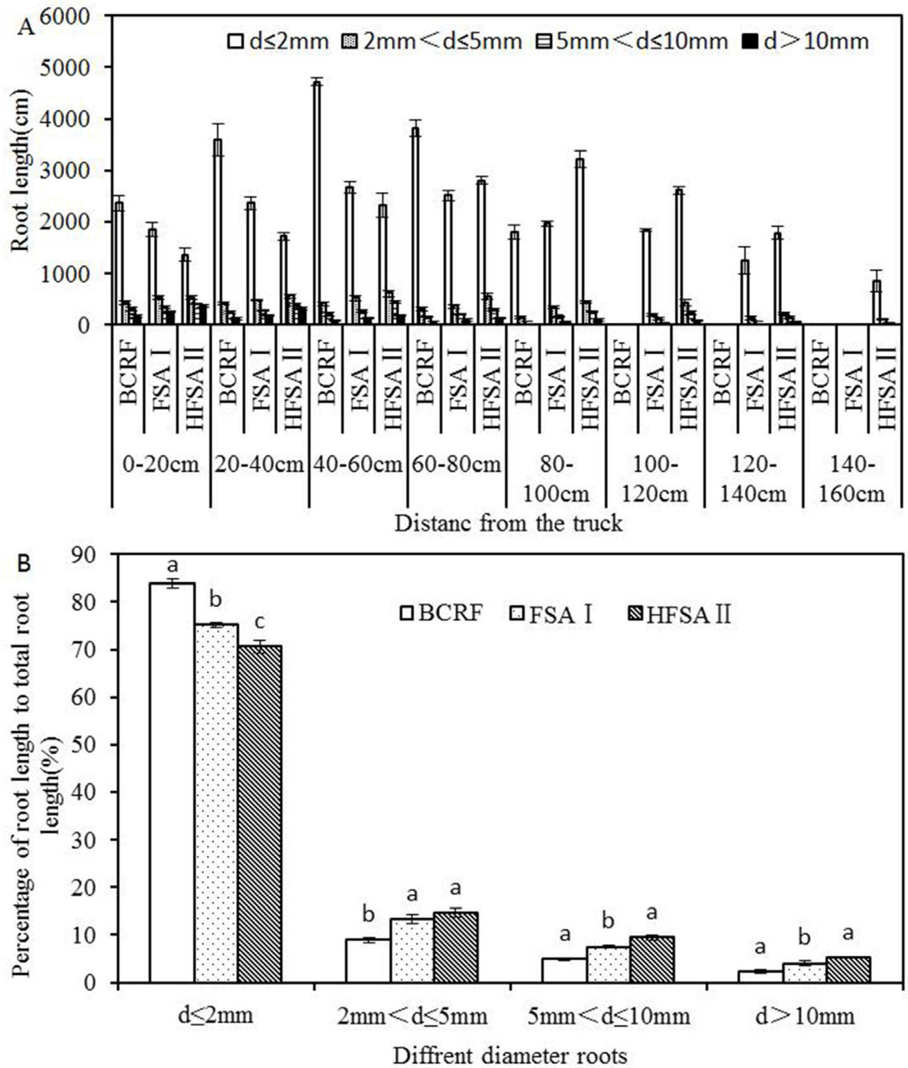

Fig. 16. The effect of BCRF on root growth of peach trees.
BCRF: bag-controlled release fertilizer (95 g/bag) with common composite mixed fertilizer. Urea, diammonium hydrogen phosphate, and potassium sulfate in a ratio of 41:14:40 ($N:P_2O_5:K_2O$). FSA I: equal amount ditch application once: with equivalent amount of common composite fertilizer mixed in the same ratio of $N:P_2O_5:K_2O$ as the BCRF. HFSA II: high-dose double ditch application twice with double amount of common composite fertilizer mixed in the same ratio of $N:P_2O_5:K_2O$ as the BCRF. Each point represents the mean ± standard error (n = 3). Different lowercase letters indicate a significant difference between treatments (P<5%).

Nitrogen availability in roots can affect the root growth rate and root development (Hodge, 2006). An appropriate amount of ammonium and nitrate nitrogen can increase the number of branches of the main root (Boukcim et al., 2006). Our results showed that soil nutrients were more stable under the BCRF treatment, which facilitated root system development and growth in autumn. Appropriate amount and stable supply of available nitrogen could extend the root life of peach trees which is in agreement with Baldi et al. (2010). This reduces root extension and leads to more concentrated root system distribution. When peach tree roots are at a state of stable nutrient supply throughout the year, root system growth is relatively concentrated, which is beneficial for extending the lifespan of roots and decreasing nutrient consumption required for root synthesis. BCRF was beneficial for the development of fine roots and extension of root lifespan, resulting in the formation of a dense root system. This provides a biological foundation for efficient nutrient absorption in peach trees.

3.9. BCRF can increase nitrogen absorption and use efficiency in peach trees

A large amount of chemical fertilizer has increased production to a certain extent, but due to excessive fertilization, improper fertilization, and the type of fertilizer used, a large amount of nitrogen is lost and nitrogen absorption and use efficiency is low in peach trees. BCRF can significantly increase the nitrogen utilization rate from fertilizer (Fig. 17) and provides a guarantee for reducing the amount of nitrogen fertilizer applied. Results showed that the nitrogen utilization rate of BCRF-treated trees were 1.39 and 1.81 times that of FSA I and HFSA II treatments, respectively. BCRF releases nutrients slowly and changes in soil moisture have fewer effects on absorption by fruit trees. Spreading application of fertilizers leads to a drastic increase in available nutrient concentration within a short period of time. However, high concentrations of available nutrients are not rapidly absorbed by plants, and most are lost by NH_3 volatilization, nitrification, denitrification, or entry into

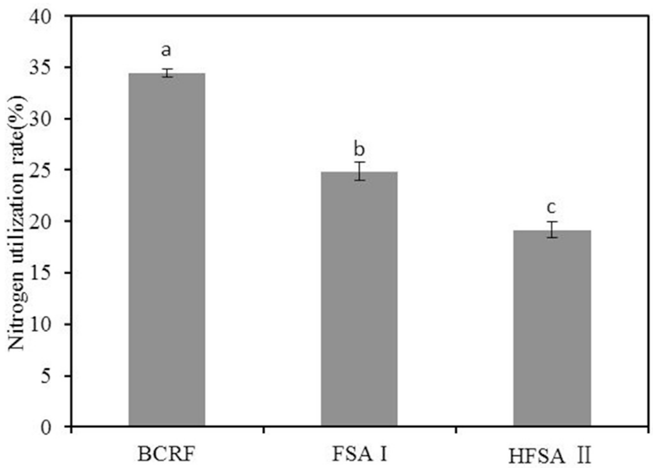

Fig. 17. Effect of BCRF on nitrogen utilization rate of peach trees. BCRF: bag-controlled release fertilizer (95 g/bag) with common composite mixed fertilizer. Urea, diammonium hydrogen phosphate, and potassium sulfate in a ratio of 41:14:40 ($N:P_2O_5:K_2O$). FSA I: equal amount ditch application once: with equivalent amount of common composite fertilizer mixed in the same ratio of $N:P_2O_5:K_2O$ as the BCRF. HFSA II: high-dose double ditch application twice with double amount of common composite fertilizer mixed in the same ratio of $N:P_2O_5:K_2O$ as the BCRF. Each point represents the mean ± standard error (n = 3). Different lowercase letters indicate a significant difference between treatments (P<5%).

the groundwater system. The first growth peak of peach tree roots ended at mid-late June. During that time, from collection of fertilizer bags, we can see that a large number of fine roots were present around the fertilizer bag under the BCRF treatment. These fine roots surround the fertilizer bag and facilitate the complete absorption of nitrogen released from the bag. It was difficult to observe fine roots near the application site in the year in which fertilizers were applied by spreading. This may be due to overly high nutrient concentrations in the soil, resulting in fine roots dying. In addition, researchers have report that as the season progress, the nitrogen that is absorbed by the root system becomes more and more important to the tree (Sanchez et al., 1990; Rufat and Dejong, 2001). BCRF can supply nitrogen fertilizer at the later stage of growth in peach trees and improve nitrogen absorption in roots, thereby increasing nitrogen absorption and use efficiency.

3.10. BCRF can improve fruit quality in peaches

After five years of continuous BCRF application, fruit quality in peaches was improved. From Table 5, we can see that, the soluble solid content, soluble solid/acid in the BCRF and FSA I treatments were significantly higher than those of the HFSA II treatment while titratable acid content was significantly lower than the HFSA II treatment. At the same time, the mean differences in the different quality markers between the BCRF and FSA I treatments were not significant. However, the mechanism by which BCRF improved the quality of peach tree fruit is still unclear.

Table 5
The individual fruit quality under different fertilization modes.

Treatment	Soluble solid content (%)	Titrable acids (%)	Soluble solid/acid
BCRF	12.29a	0.189b	65.03a
FSA I	12.13a	0.186b	65.22a
HFSA II	10.23b	0.248a	41.25b

BCRF: bag-controlled release fertilizer (95 g/bag) with ordinary composite mixed fertilizer. Urea, diammonium hydrogen phosphate, and potassium sulfate in a ratio of 41:14:40 ($N:P_2O_5:K_2O$). FSA I: equal amount ditch application once: equal amount of common composite fertilizer mixed in the same ratio of $N:P_2O_5:K_2O$ as the BCRF. HFSA II: high-dose double ditch application twice with double amount of common composite fertilizer mixed in the same ratio of $N:P_2O_5:K_2O$ as the BCRF. Different lower-case letters indicate a significant difference between treatments (P<5%).

The goal of slow-release fertilizer development is a slow-release fertilizer that is completely consistent with nutrient requirements of a certain type of fruit tree. However, since because the nutrient requirements of different species are different, even the same species needs to be completely different in nutrient requirements under different site conditions. The direction of future research is to develop slow-release fertilizers that can match the nutrient requirements of different tree species and different soil fertility statuses. In addition, BCRF could not achieve the exact match between the nutrient supply of controlled release fertilizer and the absorption of fruit trees. Therefore, further research is needed to synchronize the nutrient supply of BCRF with the absorption of fruit trees in time and space.

3.11. Analysis of the potential of reducing application of nitrogen fertilizer when BCRFs were used in major peach-producing areas in China

We have applied BCRFs for 5–8 years in the demonstration peach orchards in China. Through analysis, we found that if BCRFs were used in fertilizer application in peach orchards in major producing areas in China, the potential for reducing the amount of nitrogen fertilizers used is huge. BCRF will not only reduce the amount of nitrogen fertilizers applied but also correspondingly reduce the amount of phosphorus and potassium fertilizers used. As shown in Table 6, compared with common fertilizer application methods (application of common composite fertilizer), the use of BCRF can reduce the amount of nitrogen fertilizers used by 69.1–81.7%, 69.0–78.4%, and 65.3–76.2% for early-maturing, medium-maturing, and late-maturing peach varieties, respectively.

We conducted a corresponding financial analysis of the investment in fertilizers in peach orchards. The investment of BCRF in the demonstration peach orchards was 357.6, 476.7 and 595.9 USD·ha $^{-1}$ (converted to composite fertilizer of BCRF at 1248.4 USD· t^{-1} as priced on the market of China in April of 2019) for early-maturing, medium-maturing, and late-maturing peach varieties, respectively. The investment of common composite fertilizer in common fertilization mode peach orchards was 522.1, 587.4 and 669.8 USD·ha^{-1} in Shandong provinces, 601.1, 680.2 and 772.9 USD· ha $^{-1}$ in Hebei provinces, 505.0, 566.8 and 642.4 USD· ha $^{-1}$ in Henan provinces, 0, 669.8 and 687.0 USD·ha $^{-1}$ in Liaoning provinces, 357.3, 474.0 and 580.5 USD·ha^{-1} in Shanxi provinces, 453.4, 505.0 and 529.0 USD·ha^{-1} in Gansu provinces (converted to composite fertilizer at 341.8 USD· t^{-1} as priced on the market of China in April of 2019) for early-maturing, medium-maturing, and late-maturing peach varieties, respectively. The results show that the application of BCRF can significantly reduce the cost of fertilizer input in peach orchards. The cost of fertilization labor was not taken into account. Considering that the amount of labor for applying BCRF is much lower than that of applying common fertilizer, BCRF can significantly reduce the cost of fertilization in peach orchards.

To combat the overuse of chemical fertilizers, China has launched a plan of prohibiting any further increase in chemical fertilizers since 2015 (Wang et al., 2018), and the application of bag-controlled fertilizer is conducive to the implementation of the program. From our results we can see that comparison of demonstration peach orchards in Shandong, Hebei, Henan, Liaoning, Shaanxi, and Gansu provinces and in which BCRFs were used with peach orchards in which common fertilizer application methods were used showed that the amount of nutrient fertilizers added was significantly reduced, while yield was not decreased. A study reported that yield under multiple fertilizer application is not

Table 6
Nitrogen applied amount in the main peach producing areas of China.

Fertilization mode	Area	Variety type	Yield ($kg \cdot ha^{-1}$)	Number of farmers	Nitrogen input ($kg \cdot ha^{-1}$)
BCRF	Demonstration peach orchard	Early maturing variety	33463.4	21	64.4
		Medium maturing variety	41293.1	20	85.9
		Late maturing variety	48702.7	27	107.4
Common fertilization mode	SD	Early maturing variety	33238.4	87	305.5
		Medium maturing variety	41173.1	106	343.7
		Late maturing variety	48852.7	56	391.9
	HB	Early maturing variety	33103.4	62	351.7
		Medium maturing variety	40333.1	59	398.0
		Late maturing variety	47832.8	42	452.2
	HN	Early maturing variety	31333.5	76	295.5
		Medium maturing variety	37783.2	58	331.6
		Late maturing variety	45357.9	46	375.9
	LN	Early maturing variety	0	0	0
		Medium maturing variety	37460.8	21	391.9
		Late maturing variety	41293.1	7	402.0
	SX	Early maturing variety	30193.6	23	209.0
		Medium maturing variety	37273.3	26	277.4
		Late maturing variety	44787.9	18	339.7
	GS	Early maturing variety	28873.6	19	265.3
		Medium maturing variety	37138.3	31	295.5
		Late maturing variety	45267.9	14	309.5

BCRF: bag-controlled release fertilizer (95 g/bag) with ordinary composite mixed fertilizer. Urea, diammonium hydrogen phosphate, and potassium sulfate in a ratio of 41:14:40 ($N:P_2O_5:K_2O$). Some farmers planted more than one type of variety. SD, HB, HN, LN, SX, and GS denote the peach plantation sites in Shandong, Hebei, Henan, Liaoning, Shanxi and Gansu provinces, respectively. Demonstration parks were distributed in Shandong, Hebei, Henan, Liaoning, Shanxi, and Gansu provinces.

higher than a single application. The main reason for this is that multiple spreading applications stimulate vegetative growth of fruit trees, which cannot normally convert to reproductive growth, resulting in reduced yield. This is not due to insufficient available nitrogen but rather conversion of available nitrogen that should be used for fruit components into growth of branches (Meheriuk et al., 1995). In addition, this can significantly reduce environmental pollution problems caused by excessive application of chemical fertilizers. Hence, it can be seen that BCRFs have huge potential in reducing the amount of nitrogen fertilizers applied in peach orchards in China.

Excessive fertilizer application can cause many problems, such as decreased fertilizer utilization rate, accumulation of large amounts of nitrates in the soil environment, and soil salinization and water pollution (Samonte et al., 2006). For a long time, China's cultivated land, particularly peach orchards, are in a highly intensive production state, and irrational use of large amounts of chemical fertilizers is a widespread problem. Only by employing sustainable development strategies and establishing efficient soil fertility and water management models for peach ecology can the amount of chemical fertilizers be decreased, minimizing the amount of nitrogen emissions from orchards, as well as minimizing the environmental effects of fertilizer application to achieve a balance between agricultural economic, social, and ecological benefits.

Our research results show that in China's major peach producing areas, under the premise of not reducing yield from peach orchards, the application of BCRFs can reduce the amount of nitrogen fertilizers used by 65–82% compared with common fertilizer application methods and has the potential to reduce the amount of nitrogen fertilizer used. It has been reported that repeated application of common fertilizer stimulates the vegetative growth of fruit trees, which is not conducive to reproductive growth and causes a decline in yield (Meheriuk et al., 1995). In addition, we continuously conducted a demonstration of BCRFs for six years in the apple production area of Mengyin, Shandong Province, and found that the amount of nitrogen fertilizer was significantly reduced (data is not listed). By using the sustainable development of the fruit industry as a goal, comprehensive application of controlled-release fertilizer techniques in orchards in China may be significant for improving fruit quality, improving fertilizer use efficiency, saving fertilizer resources, protecting the ecological environment of orchards, and completing sustainable production.

4. Conclusions

The current study indicated that BCRF maintains a stable supply of soil nutrients, decreases nitrogen leaching, ammonia volatilization and greenhouse gas emissions while nitrogen loss was significantly reduced. Also, BCRF would reduce the combined global warming potential at 20-, 100-, and 500-years, respectively. Application of BCRF in peach orchards promotes the formation of a dense root system of peach trees by the development of fine roots and more concentrated root distribution. ^{15}N tracer experiments showed that BCRF can significantly increase the absorption and utilization rate of nitrogen by peach trees. BCRF reduces the amount of nitrogen fertilizers applied by 65–82% over that of common fertilizer application methods without decreasing peach yield and has a huge potential for reducing the amount of nitrogen fertilizer used and reducing fertilizer input costs in peach production. This shows that BCRF has a huge application potential as a new, environmentally friendly, low-cost and efficient fertilizer for cleaner production in peach orchards.

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