Fates of applied nitrogen fertilizer after harvesting wheat on dryland soil

Jianbin Zhou[1], Bin Liang[1,2], Wei Zhao[1, 3], Mengjie Xia[1], Xueyun Yang[1]

[1]College of Natural Resources and Environment, Northwest A&F University, Yangling, Shaanxi 712100, China;
Key Laboratory of Plant Nutrition and the Agri-environment in Northwest China, Ministry of Agriculture, Yangling, Shaanxi 712100, China
[2]College of Resources and Environmental Sciences, Qingdao Agriculture University, Qingdao, Shandong 266109, China
[3]Weinan Agricultural Technology Extension Service Center, Weinan, Shaanxi 714000, China

Abstract
About one third of nitrogen (N) fertilizer is retained in the soil after crop harvest. Understanding the fate of this residual fertilizer N in soil is important for evaluating its overall use efficiency and environmental effects. In this study, the ^{15}N-labelled fertilizer was applied to winter-wheat growing in three different fertilizedsoils (No-F, no fertilizer; NPK, inorganic NPK fertilization; and MNPK, manure plus inorganic NPK fertilization) from a long-term trial (19-year) on the south edge of the Loess Plateau, China. The fate of residual ^{15}N in soils over summer fallow and the second winter-wheat growing season was followed. The amount of the residual N in the No-F soil was significantly higher than that in the NPK and MNPK soils after harvesting the first wheat crop. The forms of the residual N in the No-F soil was mainly in mineral form; and for the NPK and MNPK soils, they were mainly in organic form. The loss of ^{15}N in No-F soil over the summer fallow was as high as 33%, and significantly higher than that in the NPK soil (8%) and MNPK soil (5%). The residual ^{15}N use efficiency by the winter-wheat in the second cropping were equivalent to 9.0%, 2.0% and 2.2% of the originally applied ^{15}N. A high proportion of the residual ^{15}N was lost during the summer fallow in dryland farming. Better management of the residual N in soil during the summer fallow is required, its contribution to subsequent cropsis also deserved consideration when makingN fertilizer recommendation.

Key Words
Dryland farming, nitrogen fertilizer, residual N, N loss, loess soil

Introduction

Dryland (rainfed agriculture) areas cover about 41% of the Earth's surfacein the world, and 51% of the arable land in China. About 75% of the wheat in the world is grown in dryland farming systems (Li 2004). The application of syntheticN fertilizer significantly has increased since 1980s on the dryland farming in China.Excessive application of N fertilizer has become common; and has caused not only poor N use efficiency (NUE), but also a series of environmental problems, such asemission of nitrous oxide, groundwater pollution, and eutrophication.

Many studies found that about one third of the fertilizer N remained in the soil after crop harvest (Dang et al., 2003; Glendining et al., 1997; Ju et al 2009). To feed the increasing population, N fertilizer application in the most developing countries is still increasing, especially in China and India.As a result, the amount of residual fertilizer N in the soil after harvest will increase.The accumulation of residual fertilizer N in soil may be helpful to the build-up of soil fertility.However, high accumulation of residual N in soil increases its loss risk to groundwater and atmosphere, especially if we ignore it when making fertilizer recommendation to the following crops.

After harvesting wheat, the field is usually ploughed, and kept bare during the summer (summer fallow). The aim of summer fallow in dryland cropping is to store water and renew soil fertility(Li et al 2004).The summer fallowing period is the rainy season in North China. The residual fertilizer N in soil may leach into deeper soil. However, the quantity of residual fertilizer N lost during this period is not well known. The effect of different fertilizer managements on the fate of residual fertilizer N during the second cropping season is not well known. Therefore, we studied the fate of ^{15}N-labeled fertilizer applied to a wheat crop during the subsequent summer fallow and a second wheat crop in a micro-plot experiment on the Loess Plateau.

Methods

Study Site

The ^{15}N-labeled fertilizerexperiment was carried out in treatments of a long-term fertilizer experiment,which was initiated in 1990 at the Wuquan Research Station (34°17'51''N, 108°00'48''E) in Yangling, Shaanxi, China. The site has a temperate, semi-humid climate with a mean annual temperature of 12.9 °C; and annual precipitation and potential evaporation is 620 and 1,400 mm, respectively. The soil is classified as UdicHaplustalf in the USDA system. Main chemical and physical properties of the surface soil (0–20 cm) in 1990 were: organic C 7.3 g kg^{-1}, total N 0.9 g kg^{-1}, total P 0.6 g kg^{-1}, total K 22.8 g kg^{-1}, Olsen P 6.5 mg kg^{-1}, available K 178.7 mg kg^{-1}, and bulk density 1.3 g cm^{-3}. Winter wheat (*TriticumaestivumL.*) is usually sown in early October, and harvested in early June the following year. After harvesting winter wheat, the field is fallowed (summer fallow) until the next growing season in October.

Experimental Design

We used three fertilization treatments within the long-term experiment, i.e., (1) no fertilizer (No-F), (2) inorganic NPK fertilizers (NPK, N:P:K=135:47:56 kg/ha), (3) cattle manure (about 7.4 t/ha, dry weight) plus NPK fertilizers (MNPK) in October 2009. The fertilizers applied were urea, superphosphate, and potassium sulphate prior to sowing wheat. The total amount of N in the MNPK treatment was the same as that in the NPK treatment, but 70% of the N was from cattle manure and 30% from inorganic N fertilizer.

In each treatment, three PVC cylinders (24.5 cm diameter, 63 cm length) were pushed into the soil, with minimal soil disturbance in October 2009 before sowing wheat. About 3 cm of the cylinder was left above the soil surface to avoid water runoff and mixing with the surrounding soil. Before sowing, the topsoil (0–15 cm) in each PVC cylinder was removed, and the soil from three cylinders was mixed with ^{15}N-labeled fertilizer (urea, 19.58 atom% ^{15}N) at the rate of 165 kgN/ha, and then refilled into the corresponding cylinders. Thirty wheat seeds were sown into each PVC cylinder, and then thinned to twenty seedlings after germination. The wheat was harvested in June 2010. Soil profile samples were taken from every 10 cm interval to a depth of 100 cm soil to measure the content and ^{15}N enrichment of mineral N, non-exchangeable ammonium (fixed N) and total N in the soil profiles. The micro-plot was fallowed until 9 October 2010.Then the second wheat was planted in each micro-plot, the sowing rates and N addition rate were same as during the first cropping season; and no fertilizer was added to the No-F soil, and the urea applied was unlabelled in NPK soil and MNPK soil. The wheat was harvested in June 2011.After the summer fallow (9 October 2010)and after harvesting wheat (7 June 2011), soil profile samples were taken and measured for ^{15}N as was done after harvesting the first season wheat. The N uptake and yields of the first wheat were given by Liang et al (2013).

Analytical methods

Total N in soil was analysed by the Kjeldahl method. The Silva-Bremner method was used for determining the fixed N (non-exchangeable NH_4) in soil (Silva and Bremner 1966). Soil NH_4–N and NO_3–N contents were determined by extracting 25 g (wet weight) soil samples with 100 ml 0.5 MK_2SO_4 on a rotary shaker at 220 rpm for 30 min before filtering. The extracts were analyzed with a continuous flow analyzer. The ^{15}N abundances in the mineral N and fixed N were determined using the diffusion method described by Sebilo et al (Sebilo et al. 2004). The ^{15}N abundances in the samples were determined at the Stable Isotope Facility, University of California, Davis, USA.The content of plant N, total soil N, mineral N, or fixed N derived from the labeled fertilizer (Ndff) was calculated. The residual ^{15}N use efficiency (RNUE) was calculated as follows:

$$\text{RNUE (\%)} = N_{uptake} / R_{total1} \times 100$$

where $N_{uptake}$is the amount of ^{15}N taken up by winter-wheat in the second year and R_{total1} is the total residual ^{15}N after the first cropping season.

Results

Residual fertilizer Nin soil after harvesting wheat

The total residual ^{15}N in the 0-100 cm soil profile after wheat harvest was 116, 60, and 43 kg N/ha, and accounting for 70%, 36%, and 26% of added ^{15}N fertilizer in the No-F, NPK, and MNPK soils, respectively. The residualfertilizer ^{15}N (in organic and inorganic forms) in both the 0-20 and 20-40 cm depthsof the MNPK soil was significantly lower than that in the NPK and No-F soils (Fig 1). The residual ^{15}N at 40-60 cm depth was significantly lower in the NPK and MNPK soil than in the No-F soil.

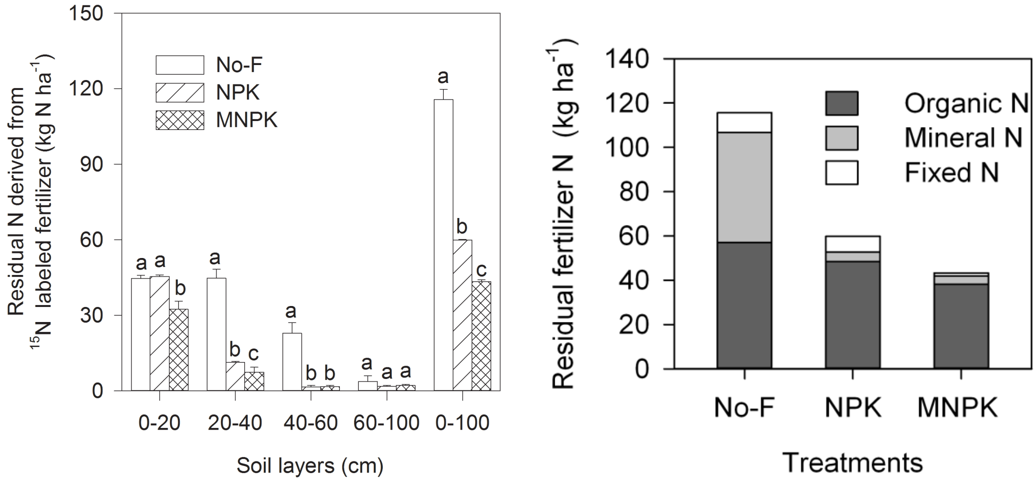

Fig 1Residual fertilizer^{15}N within the 0-100 cm soil profiles (left),and its forms after wheat harvest (right) (No-F, no fertilization; NPK, inorganic NPK fertilization; and MNPK, manure plus inorganic NPK).

The forms of the residual fertilizer N in the No-F soil were significantly different from that in the NPK and MNPK soils. In the No-F soil residual fertilizer N in mineral form was 49.8 kg/ha, accounting for 43.0% of the residual fertilizer N after the first cropping season; for NPK and MNPK soils only 4.4 and 3.7 kg/ha remained, accounting for 7.4% and 8.6% of the residual fertilizer N. In the NPK and MNPK soils 81% and 88% of the residual fertilizer was in the form of organic N. The residual fertilizer N in organic forms was higher in the NPK soil (48 kg/ha) than in the MNPK soil (38 kg/ha). The residual fertilizer N in fixed N form was significantly lower in the MNPK soil (1.5 kg/ha) than in the NPK (7.0 kg/ha), and the No-F soil (8.9 kg/ha).

Changes of residual N during summer fallow

After the summer fallow, the residual fertilizer N in the 0-100 cm soil depth of the No-F soil decreased by 55 kg/ha, which accounted for about of 33% of the originally applied fertilizer N. In contrast, the residual fertilizer N in the NPK and MNPK soils decreased by 13 and 8 kg/ha, respectively, which accounted for 8% and 5% of the applied fertilizer N (Fig. 2).

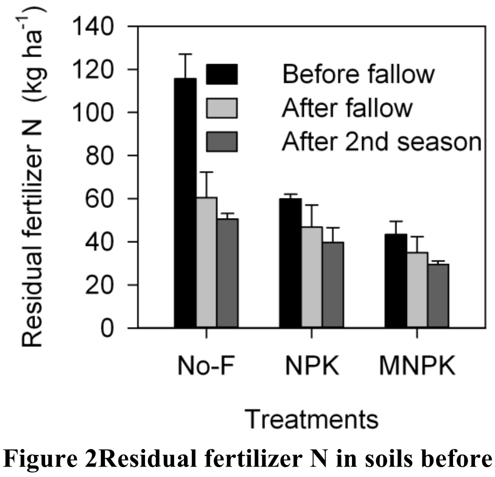

Figure 2Residual fertilizer N in soils before and after the summer fallow and after harvesting the second wheat(No-F, no fertilization; NPK, inorganic NPK fertilization; and MNPK, manure plus inorganic NPK).

Availability of the residual N to the subsequent crops

The ^{15}N labelled fertilizer N uptake (^{15}N uptake) by the second winter wheat in the No-F soil was significantly ($P<0.05$) greater than that in the NPK and MNPK soils (Table 1). The residual ^{15}N use efficiency(RNUE) in the No-F, NPK and MNPK soils was 13%, 6% and 8%,equivalent to 9%, 2% and 2% of the originally applied 15N (Table 1). Compared to the NPK soil, the MNPK soil significantly increased the total ^{15}N uptake by winter wheat in two growing seasons.

Table 1The^{15}N labeled fertilizer N uptake (^{15}N uptake) in grains and plants (including leaves and stems), and residual ^{15}N use efficiency (RNUE) by the second winter wheat.

Treatments	^{15}N uptake (kg/ha)		RNUE (%)	Total ^{15}Nuptake in two growing seasons (kg/ha)
	Grains	Plants		
No-F	11.2±2.7 a	13.3±3.0 a	12.8±0.9 a	47.5±3.4c
NPK	2.6±0.7 b	3.3±0.8 b	5.6±1.3 b	99.8±0.1b
MNPK	2.9±0.1 b	3.7±0.1 b	8.5±0.4 b	110.0±1.4 a

*Values are means ± SD (n=3). Values with different lowercase letters within a column are statistically significantly different at P < 0.05.

Residual fertilizer N in soil after harvesting the second wheat

After harvesting the second season wheat, the residual fertilizer N was highest in the No-F soil (31% of the applied ^{15}N labelled fertilizer N), and lowest in the MNPK soil (18% of the applied ^{15}N labelled fertilizer N) (Fig. 2). Over 80% of the residual ^{15}N was in the 0-40 cm soil layers in the three soils.

Total ^{15}N recovery was calculated as the sum of the ^{15}N uptake by the winter wheat and the residual ^{15}N in the 0-100 cm soil profile. During the first cropping season, total ^{15}N recovery was more than 90% in the three soils; and there were no significant (P<0.05) differences among the three soils. After the summer fallow, the total ^{15}N recovery in the NPK and MNPK soils was 87% and 86%, respectively, and significantly (P<0.05) greater than in the No-F soil (56%). After the second cropping season, the total ^{15}N recovery in the No-F, NPK, and MNPK soils were 60%, 85%, and 85%, respectively. Scarcely any ^{15}N was lost during the second cropping season.

Conclusion

One of the most important findings of this study is that the loss of the residual fertilizer N in differently fertilized soils was very high during the summer fallow period. The application rate of N fertilizer in many rapidly developing countries is still increasing. Therefore, the residual N in soil after harvesting crop will also increase. To solve this problem, one option is that more attention should be paid to matching N supply to its demand in the first crops to avoid the residual N being left in the soil. A second option is to better manage the residual N during the summer fallow, for example, planting catch crops, and straw mulching, to decrease the loss of residual N. Residual ^{15}N use efficiency by the second winter-wheat was 6-13%. This indicates that the uptake of residual N should be taken into account when formulating fertilizer advice for the second crop especially where large amounts have been left by the first crop.

Acknowledgments

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