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ORIGINAL ARTICLE

Residual effects of fertilizer N response to split N applications in semiarid farmland

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Abstract A better understanding of residual N fate is important for N management in agricultural production. The N application rate and time may dramatically influence N recovery in the plant–soil system, in turn affecting residual N uptake by subsequent crops. A 3-year field experiment was conducted in plastic-mulched maize in semiarid farmland. ^{15}N-labeled urea was applied to microplots with a single application (100% before sowing, N1), two splits (4:6 at sowing and eight-leaf stages, N2), and three splits (4:3:3 at sowing, eight-leaf, and silking stages, N3), and the fate of residual fertilizer N in soils over the following two cropping seasons was examined. Approximately 14.6–18.7% and 5.4–5.8% of labelled fertilizer N were recovered by maize in the second and the third seasons, respectively, with the cumulative recovery efficiency reaching 47.6–60.8% over 3 years. Applying N with three splits significantly increased residual fertilizer N recovery by 24.6% in the second cropping season compared to N1 and N2. About 22.7–32.4% and 15–21% of total labelled N applied was residual in the 0–2 m soil layer after the second- and the third-season harvest, respectively, with the higher residual amount from split N applications. In conclusion, split N applications significantly increased the cumulative fertilizer N recovery in the plant–soil system while decrease the potential losses over 3 years, due to the higher recovery efficiency and the lower N losses from topdressed N.

Keywords ^{15}N · Residual N fate · N application time · N recovery efficiency · Residual N distribution

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Introduction

As the largest source of anthropogenic reactive N worldwide, synthetic N fertilizer has supported the world's rapidly expanding population during the last few decades (Fowler et al. 2013a, b; Tilman et al. 2011). However, large amounts of external N inputs have contributed to not only the decrease of N recovery efficiency (RE) but also severe environmental degradation with a high potential N loss in many pathways, such as the release of greenhouse gases,

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surface and groundwater contamination and soil quality degradation (Guo et al. 2010; Ju et al. 2009; Shcherbak et al. 2014). China is the largest user of fertilizer N in the world, and many field experiments reported low NRE of 30–35% in the 1990s (Zhu and Chen 2002) and 26–28% in 2001–2005 for major cereal crops (Zhang et al. 2007), considerably lower than the 52% in the United States and 68% in Europe (Ladha et al. 2005). Although it appears that approximately 70% of N fertilizer has been wasted in China every year, that is not the case. The residual effect in subsequent seasons of fertilizer N remaining in soil has been confirmed by previous studies, with the RE varying from 2 to 20% (Bhogal et al. 2000; Ichir et al. 2003; Liang et al. 2013; Liu et al. 2015; Macdonald et al. 2002). The large variation in the RE of residual N may be attributed to different cropping systems, environmental conditions in different regions, and different management practices (Christian et al. 2006; Ferchaud et al. 2016; Grant et al. 2016; Ichir et al. 2003; Pilbeam et al. 2002).

Split N applications are believed to significantly increase grain yields, plant N uptake, and the NRE by improving the temporal synchrony between crop N demand and soil N availability (Ribaudo et al. 2011; Wang et al. 2016a, b). Split N applications also influence the distribution of residual N in the soil profile layer (Shi et al. 2012; Wang et al. 2016b). For example, Shi et al. (2012) reported that the residual amount of topdressed N was higher than that of basal N in the 0–0.6 m soil layer, but an inverse trend was found in the 0.6–1.0 m soil layer. In a previous study (Wang et al. 2016a), we investigated the fate of ^{15}N-labeled fertilizer with different split N applications as well as the basal and topdressed N applied at different stages. Although there was no difference between split N applications on residual N in the 0–2 m soil layer, the residual amount from topdressed N was higher than that from basal N, and the topdressed N at silking stage (T_{R1}-N) showed the highest residual rate when N was applied with three splits, especially in the 0–0.4 m soil layer (Wang et al. 2016a). A previous 2-year study in semiarid farmland reported that the majority of maize roots were distributed in the top 0.4 m of soil (Xiao et al. 2016); furthermore, a 5-year field trial in the Swiss midlands showed that approximately 80% of the total root length of maize was in the layer from 0 to 0.4 m, with maximum values from 0.05 to 0.10 m (Qin et al. 2006). A better spatial matching between N in soil layer and root distribution might promote N uptake by plants. Therefore, we speculated that the residual topdressed N would be more available to be taken up by subsequent crops. In addition, fertilizer N exceeding plant demand would be quickly immobilized by microorganisms, thus protecting N from loss pathways, and the immobilized N could be subsequently remineralized and taken up by plants (Sugihara et al. 2010). The mineralization-immobilization turnover (MIT) of N in soil has a major influence on the amount of soil-available N (Myrold and Bottomley 2008). The application rate and timing of N application might influence the MIT dramatically, which in turn affects plant N uptake.

Plastic mulching has been widely adopted in arid and semiarid regions (Li et al. 1999; Zhou et al. 2009) due to its prominent role in increasing crop yields (Liu et al. 2009; Sharma et al. 2011). As a physical barrier, plastic mulching influences the exchanges of energy and matter between the atmosphere and soil, for instance, by preventing soil water evaporation (Li et al. 2004), increasing the soil surface temperature (Liu et al. 2014), decreasing N leaching losses from the root zone (Anikwe et al. 2007), and promoting the mineralization of soil organic N (Li et al. 2004). As consequence, the behavior of fertilizer N may change under plastic mulch. However, the fate of fertilizer N, especially the multi-season residual effect of fertilizer N, under plastic mulch has seldom been studied (Liu et al. 2015). In an earlier paper (Wang et al. 2016a), we presented data on the in-season RE of ^{15}N-labeled fertilizer (27.9–39.1%) with different split applications of N to mulched maize in semiarid farmland, and we hypothesized that a sizable portion of the residual fertilizer N remaining in soil after the first-season harvest could be utilized by the subsequent crops due to the lower N leaching and the higher N mineralization under plastic film mulching; furthermore, split N applications would influence the residual N recovery in the plant–soil system. To confirm our hypothesis, the fate of residual fertilizer N in soils over the following two cropping seasons was traced under different N split applications. The objectives of the present study were to investigate the fate of fertilizer N over 3 years in plastic-mulched maize system and to explore the response of fertilizer N residual effects to split N applications.

Materials and methods

Site description

The field experiments were conducted from 2013 to 2015 at the Changwu Agricultural and Ecological Experimental Station of the Chinese Academy of Sciences (35.28°N, 107.88°E, 1200 m altitude), which is located in a typical dryland farming area on the Loess Plateau of northwestern China. The annual mean air temperature is 10.4 °C, and the average annual precipitation was 570 mm from 2013 to 2015, with 75% of the total amount of rain falling during the maize growth season (Fig. 1). The land use of the plots was one crop of maize per year before the experiment started in 2013. According to the American system of soil classification, the soil at the experiment site is a Cumulic Haplustoll that developed from loess deposits (Soil Survey Staff 2010). Before fertilization in 2013, the soil properties in the top 0.2 m were as follows: bulk density, 1.3 Mg m^{-3}; pH 8.3; organic C, 8.1 g kg^{-1}; total N, 1.0 g kg^{-1}; available phosphorus (Olsen-P), 21.5 mg kg^{-1}; available potassium (NH_4-OAc-K), 135.2 mg kg^{-1}; and mineral N (NO_3^-–N + NH_4^+–N), 28.3 mg kg^{-1}.

Experimental design

Three treatments were designed with different fertilizer N splits, which performed through three growing seasons: (1) 100% N applied before sowing (N1); (2) N applied at the sowing and eight-leaf (V8) stages at a ratio of 4:6 (N2); and (3) N applied at the sowing, eight-leaf (V8) and silking (R1) stages at a ratio of 4:3:3 (N3). The same rate of 225 kg N ha^{-1} was applied in all treatments, a common application rate in this study region (Zhou et al. 2012). The area of each main plot was 90 m^2 (6 m × 15 m), arranged in a complete randomized block design with three replications. N fertilizer was applied in the form of urea (46% N), part of which was manually distributed over the soil surface prior to sowing and then plowed into the soil at a depth of 0.15–0.20 m as a basal dressing; applications at V8 and R1 were made with a hole-sowing machine following precipitation. In each plot, 40 kg P ha^{-1} (calcium superphosphate, P_2O_5, 12%) and 80 kg K ha^{-1} (potassium sulfate, K_2O, 45%) were applied together with basal N before sowing. A high-yielding maize hybrid (Pioneer 335) was used in this study, with a plant density of 65,000 plants ha^{-1}. The maize seeds were sown to a 0.05-m depth using a hand-powered hole-drilling machine on 21, 28 and 26 April, and maize plants were harvested on 5, 19 and 19 September in 2013, 2014 and 2015, respectively. All treatments involved alternating a wide (0.6 m wide, 0.1 m high) and narrow (0.4 m wide, 0.15 m high) ridge and a furrow. Both ridges were manually mulched with 0.008 mm-thickness transparent polyethylene plastic film after being constructed. The joint of the two pieces of film was in the midline of the broad ridge, and the joint was secured by placing soil on top of the film.

To monitor the fate of ^{15}N-labeled fertilizer, microplots (1 m × 2 m size) were established within each plot and were bordered by 0.5-m-high galvanized sheet iron inserted into the soil to a depth of 0.45 m and exposed for 0.05 m on the surface to prevent runoff and lateral contamination. To trace the fate of fertilizer N applied at every growth stage, one, two, and three microplots were established in each plot of treatments N1, N2, and N3, respectively. ^{15}N-labeled urea (10.14 at%, provided by the Shanghai Chem-Industry Institute) was applied to the microplots using the same dose applied to the corresponding main plot in the first cropping season, and then conventional urea was used in the following seasons. Detailed ^{15}N-labeled fertilizer application schemes are shown in Table 1. The basal and topdressed N were applied to the microplot using the method described by Wang et al. (2016a).

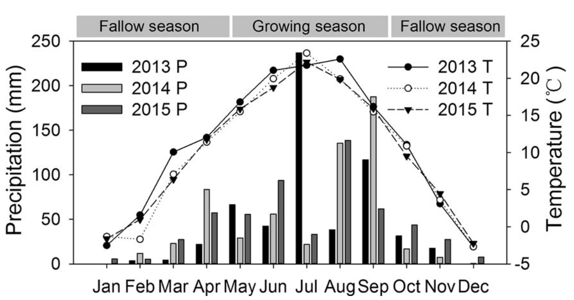

Fig. 1 Monthly precipitation and mean temperatures from 2013 to 2015. MS and FS denote the maize growing season and fallow season, respectively

Plant and soil sampling and analysis

Three evenly growing plants in each microplot were harvested close to the ground in each cropping season

Table 1 Nitrogen application stages and ratios of different treatments

Treatment		Sowing (%)	V8	R1
N1		100*	0	0
N2	I	40*	60%	0
	II	40	60%*	0
N3	I	40*	30%	30%
	II	40	30%*	30%
	III	40	30%	30%*

*^{15}N-labeled urea was applied in the first cropping season in 2013, and then conventional urea was used in the following seasons. V8 and R1 denote N applications at the eight-leaf stage and the silking stage, respectively

and were then separated into leaf, stem, bract, ear axis, and grain. The remained crop stubble (mainly roots) in the soil were broken up with shovels in situ and mixed into the soil before sowing the next year to avoid the ^{15}N being taken out of the soil-crop system. The dry weight was determined after drying at 70 °C to a constant weight. An aliquot of each dry sample was ground (< 0.15 mm) with a ball mill for total N content and isotopic analyses. The total N in plants was analyzed using the Kjeldahl method. Soil samples were taken to a depth of 2 m using a 0.04-m-diameter soil auger at 0.2-m intervals after maize harvests in each cropping season. Three sampling sites were selected and then mixed into one sample for each microplot. The soil samples were air dried and then ground through a 0.15-mm sieve. Total N in the soil was determined using a permanganate-reduced iron modification of the Kjeldahl method in order to include nitrate and nitrite (Bremner and Mulvaney 1982). The ^{15}N enrichment in soil and plant samples was determined using an isotope mass spectrometer (MAT-253, Thermo Fisher, USA) at the State Key Laboratory of Soil Erosion and Dryland Farming on the Loess Plateau, Chinese Academy of Sciences and Ministry of Water Resources. The natural abundances of ^{15}N in the soil and plants were also measured.

Calculations and statistical analysis

The percentage of N derived from fertilizer N (Ndff, %) was calculated according to the following equation:

$$\text{Ndff}\,(\%) = \text{at}\%^{15}\text{N excess in plant or soil/at}\%^{15}\text{N excess in fertilizer} \times 100 \tag{1}$$

N fertilizer accumulation and recovery in maize and soil were calculated with the following equations:

$$\text{Plant total N}\left(\text{kg ha}^{-1}\right) = \text{plant dry matter}\left(\text{kg ha}^{-1}\right) \times \text{N content}\left(\text{g kg}^{-1}\right)/1000 \tag{2}$$

$$\text{Plant N from fertilizer}\left(\text{kg ha}^{-1}\right) = (2) \times \text{Ndff}_{\text{plant}} \tag{3}$$

$$\text{Residual N in soil}\left(\text{kg ha}^{-1}\right) = \text{soil depth (m)} \times \text{soil bulk density}\left(\text{Mg m}^{-3}\right) \times \text{N content}\left(\text{g kg}^{-1}\right) \times \text{Ndff}_{\text{soil}} \times 10{,}000 \tag{4}$$

$$\text{N recovery efficiency}\,(\%) = (3)/\text{N application rates}\left(\text{kg ha}^{-1}\right) \times 100 \tag{5}$$

$$\text{N residual rate}\,(\%) = (4)/\text{N application rates}\left(\text{kg ha}^{-1}\right) \times 100 \tag{6}$$

$$\text{Potential N losses}\,(\%) = 100 - (5) - (6) \tag{7}$$

Statistical analyses were conducted using the ANOVA procedure in SPSS 20.0. Treatments were compared via the least significant difference (LSD) test at the 5% level. Graphs were produced with SigmaPlot 12.5.

Results

Residual fertilizer N recovery by subsequent crops

As reported in our previous paper, approximately half of the total fertilizer N input remained in the 0–2 m soil layer after the first cropping season (Fig. 2a, d) (Wang et al. 2016a). In this study, the fate of residual N was followed in the second and third cropping seasons. The results showed that there were still sizeable portions of the fertilizer N applied initially

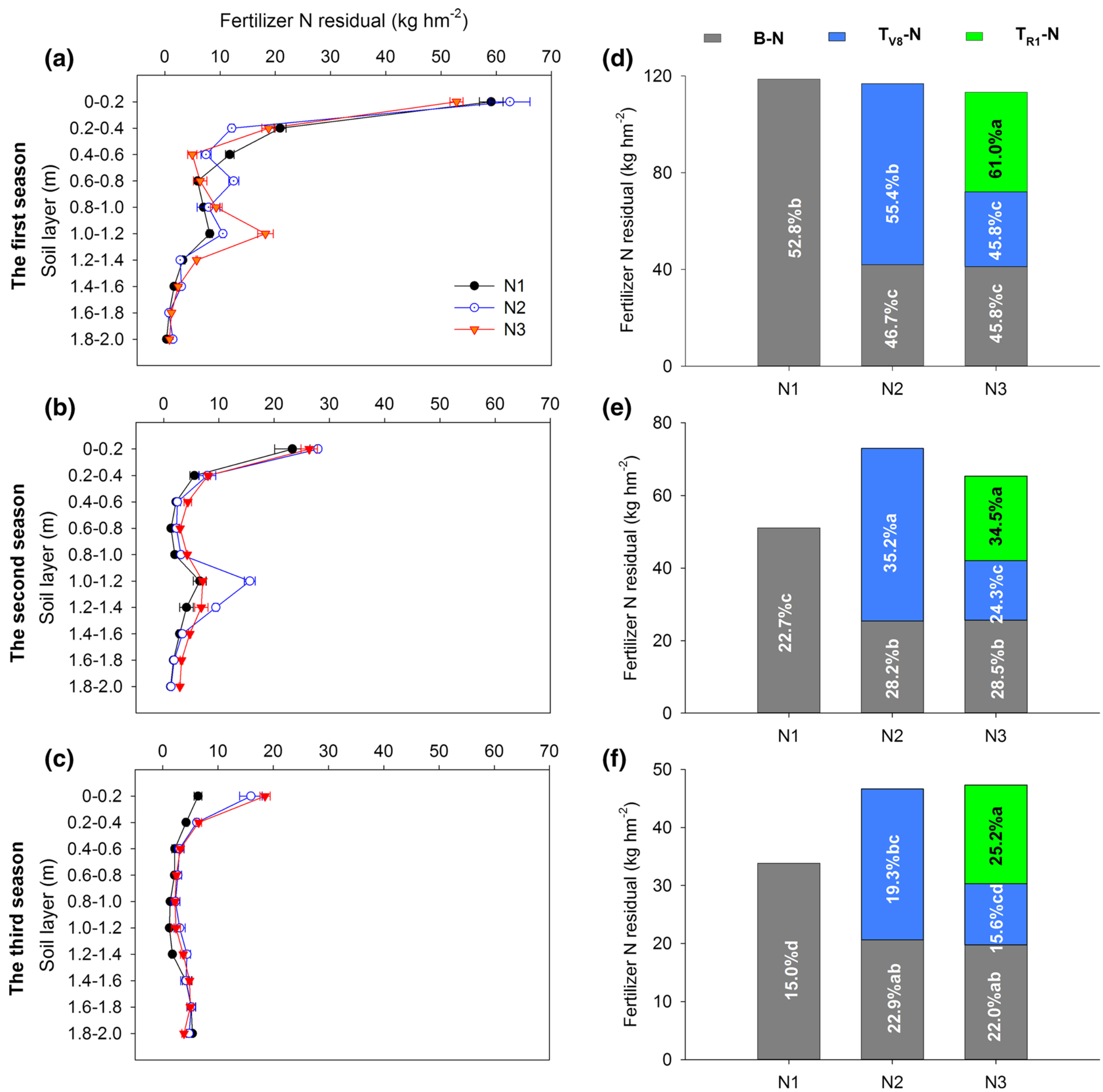

Fig. 2 The total amount and distributions of residual fertilizer N in the 0–2 m soil layer of each of the three treatments after the harvests in the first (**a**, **d**), second (**b**, **e**), and third (**c**, **f**) seasons. Error bars are standard errors of means (n = 3); The percentages on the bars denote residual rates of fertilizer N, and different lowercase letters following percentages indicate a significant difference ($p < 0.05$); B denotes basal N; T_{V8} and T_{R1} denote topdressed N at the eight-leaf stage and the silking stage, respectively; The results after the first-season harvest (**a**, **d**) have been published in a previous paper (Wang et al. 2016a)

that could be taken up in the following two cropping seasons (Table 2). Among the three treatments, the RE of labelled fertilizer N was 14.6–18.7% in the second cropping season (equivalent to 27.7–37.1% of the residual N after the first-season harvest), with a higher RE in treatment N3. T_{R1}-N in the N3 treatment had the highest RE ($p < 0.05$) in the second cropping season compared with that applied at other stages, which resulted in a significant increase of NRE with the three-split N application (N3). Furthermore, from 5.4 to 5.8% of the initial labelled fertilizer N was recovered in the third cropping season (equivalent to

Table 2 Residual fertilizer N recovery by maize in the second and third cropping seasons

Treatments		The second season		The third season	
		Recovery amount (kg ha^{-1})	Recovery efficiency (%)	Recovery amount (kg ha^{-1})	Recovery efficiency (%)
N1	B	32.9 a	14.6 c	13.1 a	5.8 b
N2	B	12.0 d	13.3 c	3.3 d	3.7 c
	T_{V8}	22.7 b	16.8 b	8.8 b	6.5 ab
N3	B	12.6 d	14.0 c	2.9 d	3.2 c
	T_{V8}	12.1 d	18.0 b	4.8 c	7.1 a
	T_{R1}	17.4 c	25.7 a	4.6 c	6.9 a
N1		32.9 B	14.6 B	13.1 A	5.8 A
N2		34.7 B	15.4 B	12.1 A	5.4 A
N3		42.1 A	18.7 A	12.3 A	5.5 A

Different lowercase letters within a column indicate significant differences ($p < 0.05$). Different capital letters within a column indicate significant differences ($p < 0.05$). B denotes basal N; T_{V8} and T_{R1} denote topdressed N at the eight-leaf stage and the silking stage, respectively

10.4–11.0% of the residual N after the first-season harvest), dramatically lower than that in the second cropping season and no significant difference was found among split N applications. On the whole, the topdressed N produced a higher RE than basal N in the subsequent two cropping seasons (Table 2).

Amounts and distributions of residual fertilizer N in soil after each season harvest

On the whole, there were 51.1–72.9 kg ha^{-1} of fertilizer N remaining in the 0–2 m soil layer after the second-season harvest (Fig. 2e) and 33.8–47.3 kg ha^{-1} after the third-season harvest (Fig. 2f), accounting for 22.7–32.4% and 15.0–21.0% of total N applied initially, respectively. Compared to the single N application, split N applications significantly increased residual N in the 0–2 m soil layer by 35.2% and 39.1% in the second and third cropping seasons ($p < 0.05$), respectively (Fig. 2c–e). The residual N in soil mainly remained at the 0–0.4 m depth, accounting for 60.7–67.3% of the total residual amount after the first-season harvest (Fig. 2a) (Wang et al. 2016a), and then the proportion decreased gradually after the second- (47.6–56.6%) (Fig. 2b) and third- (31.3–48.8%) season harvests (Fig. 2c), due to N uptake by plants and N leaching downward. In addition, slight accumulation peaks were found in the 1.0–1.2 m soil layer after the harvests in the first two cropping seasons, while the residual N amount showed an increasing trend in the 1.4–2.0 m soil layer after the harvest in the third season (Fig. 2a–c). This result also showed a downward eluviation trend of the residual N over time, and it could be deduced that part of the N fertilizer had eluviated below a depth of 2 m.

The distributions of residual basal and topdressed N in the 0–2 m soil layer after each season's harvest are shown in Fig. 3. For the basal N (Fig. 3a–c), compared with N2 and N3 (basal N rate of 90 kg ha^{-1}), the single N application before sowing (N1, 225 kg ha^{-1}) produced markedly higher residual N in the 0–2 m soil layer ($p < 0.05$), a dramatic difference mainly generated in the 0–1 m soil layer after the first season's harvest and then shifted to the 1–2 m soil layer, with the residual basal N leaching downward. For the topdressed N (Fig. 3d–f), the residual amount dramatically increased with the N application rate ($p < 0.05$), and the accumulation peaks of residual N moved downward gradually through the cropping seasons. Furthermore, in the N3 treatment, although the same fertilizer N dose was topdressed at the V8 and R1 stages, the residual T_{R1}-N was higher than that topdressed at the V8 stage (T_{V8}-N), especially in the 0–0.4 m soil depth ($p < 0.05$) (Fig. 3d–f). These results indicated that excessive fertilization at the early growing stage would increase N leaching risk due to the higher residual amount in soil, and topdressing N at a later stage could effectively prevent fertilizer N from leaching downward, increase the

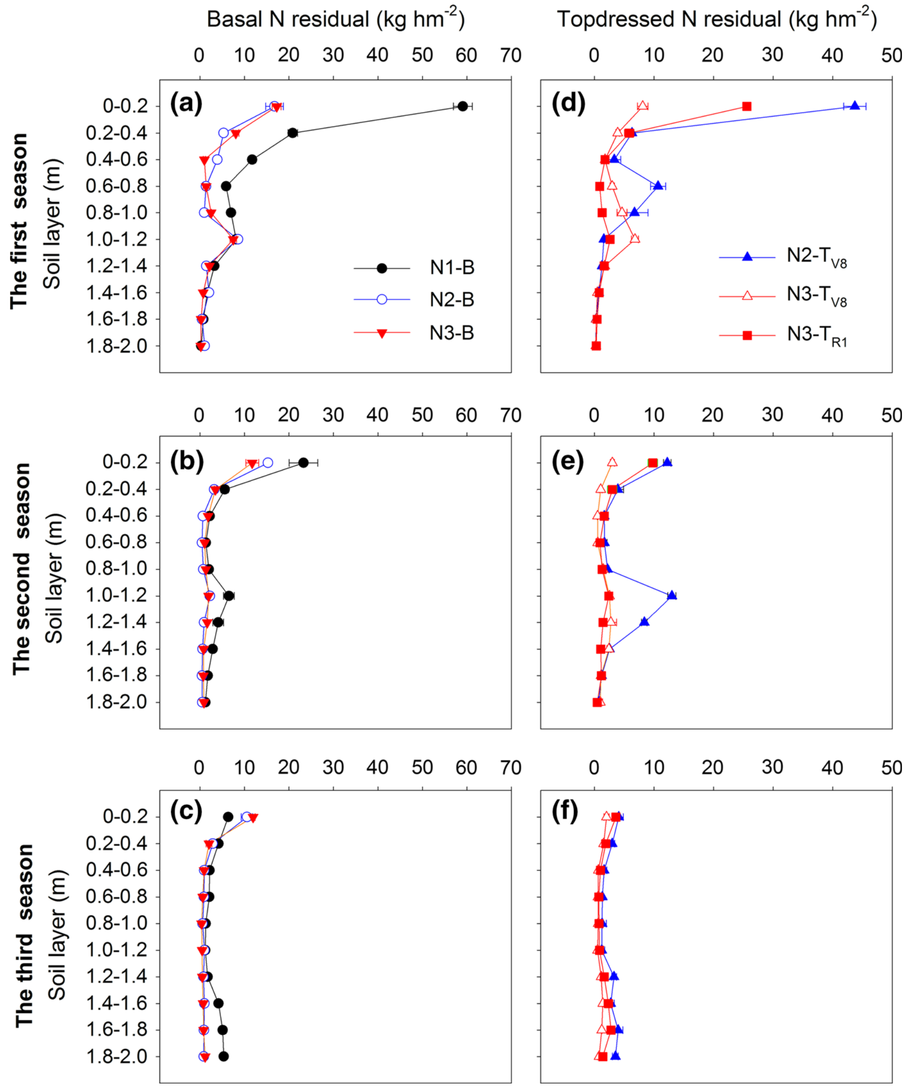

Fig. 3 Distributions of residual fertilizer N in the 0–2 m soil layer from basal (**a**–**c**) and topdressed (**d**–**f**) N after each season's harvest. Error bars are standard errors of means (n = 3); B denotes basal N; T_{V8} and T_{R1} denote topdressed N at the eight-leaf stage and the silking stage, respectively; The results after the first-season harvest (**a**, **d**) have been published in a previous paper (Wang et al. 2016a)

residual amount in the upper soil layer, and in turn increase the uptake opportunity by successive crops.

The fate of fertilizer N in 3 years

The fate of fertilizer N applied in different stages in three treatments was measured after the third-season harvest (Fig. 4). The cumulative RE values of topdressed N were from 61.5 to 70.8%, higher than that of basal N (49.5–50.9%), while there were lower potential losses in topdressed N (8.8–19.2%) than in basal N (26.2–28.5%). Compared to the basal N, cumulative residual rates decreased significantly in T_{V8}-N, while they increased significantly in T_{R1}-N. In the N3 treatment, the same N rates were topdressed at the V8 and R1 stages, although they produced the same cumulative RE, higher residual rates and lower potential losses with T_{R1}-N. This result indicated that although the in-season recovery of T_{R1}-N was relatively lower than that of T_{V8}-N, as reported in a previous study (Wang et al. 2016a), the former was more liable to be utilized by subsequent crops. On the whole, the cumulative recovery, residual, and potential losses of fertilizer N after 3 years were 47.6–60.8%, 15.0–21.0%, and 18.2–37.4%, respectively. Split N applications (N2 and N3) significantly

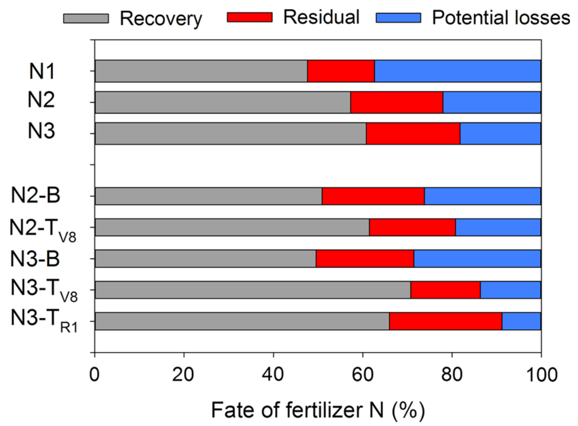

Fig. 4 The fate of ^{15}N-labeled fertilizer after 3 years. B denotes basal N; T_{V8} and T_{R1} denote topdressed N at the eight-leaf stage and the silking stage, respectively

increased the cumulative RE and residual rates, while they decreased potential losses from the plant–soil system.

Discussion

Residual fertilizer N recovery by the subsequent crops

Although the in-season NRE for major cereal crops in China was only 26–28% in 2001–2005 (Zhang et al. 2007), sizeable portions of the residual fertilizer N in soil could be taken up by successive crops (Yan et al. 2014), with the varying residual NRE in different situations, such as crop regimes, fertilization managements, and weather conditions (Bircsak et al. 2005; Ichir et al. 2003; Liang et al. 2013; Zhao et al. 2015). In the present study, 32.9–42.1 kg ha^{-1} and 12.1–13.1 kg ha^{-1} of residual N were taken up in the second and the third cropping season, accounting for 14.6–18.7% and 5.4–5.8% of the fertilizer N applied initially, respectively. Similar results were found in plastic-mulched maize by Liu et al. (2015). However, lower RE of residual fertilizer N of 2–10% and 1.7–3.5% by the second and the third crops, respectively, were reported in wheat–maize rotation system (Jia et al. 2011; Liang et al. 2013). Pilbeam et al. (2002) found only a further 3% recovered by the subsequent millet in a maize-millet rotation system and concluded that an application of fertilizer to one crop made no substantial contribution to the nutrition of the next. The higher RE of residual fertilizer N in our study may be due to the plastic mulching practice, which increased the mineral N by hindering the N leaching loss (Anikwe et al. 2007) and promoting soil organic nitrogen mineralization (Li et al. 2004). The cumulative NRE reached 47.6–60.8% after 3 years in this study (Fig. 4). Similar results were also found by previous studies (Bosshard et al. 2009; Jia et al. 2011; Yan et al. 2014).

Delaying N application to later growth stages or applying N with multiple split applications is a better strategy for N management to increase the in-season NRE by improving the synchrony between soil N availability and crop N demand (Shi et al. 2012; Wang et al. 2016a, b), while the influence of the N application time and rate on the residual effect of fertilizer N in the following seasons is less understood. In the present study, although the same residual amount was present among the three treatments after the first-season harvest (Fig. 2b) (Wang et al. 2016a), applying N with three splits significantly increased the fertilizer N recovery in the second cropping season (Table 2). The possible explanation might be that exogenous N addition could increase the mineralization of native soil organic N (Liu et al. 2017), which is the so-called "priming effect" (Kuzyakov et al. 2000). Previous studies reported that 56–88% of the residual fertilizer N in soils was in organic forms (Rimski-Korsakov et al. 2012; Zhao et al. 2015), and this part of organic N would constitute a more readily mineralizable pool (Fox 2004; Gurlevik et al. 2004), which could therefore be preferentially mineralized over the native soil organic N. In this study, it could be speculated that the residual fertilizer N in soils was mainly in organic forms. Compared to N single application, applying N with three splits in the following cropping seasons promoted the mineralization of fertilizer-derived soil organic N, in turn increased plant N uptake.

Residual amount and distributions of fertilizer N

In this study, 22.7–32.4% of the applied fertilizer N was residual in the 0–2 m soil profile after the harvest in the second season. Similar to our results, a study in a semi-humid climate area reported that the residual N remaining after the second cropping season accounted for approximately 18–31% of the initial fertilizer N (Zhao et al. 2015). However, Ichir et al. (2003)

reported a dramatically higher residual proportion of 42.8–45.6% after wheat harvest in the second year in a wheat–wheat cropping system under Mediterranean conditions, with all of the residual N remaining in the 0–0.6 m soil layer, and the 2-year cumulative NRE reached 39.5–40.5%. The different results might be attributed to the higher cumulative NRE in this study, which were 41.8–55.3% after 2 years (Table 2) (Wang et al. 2016a). Another reason might be the differences in weather conditions and soil types. The annual rainfall in the Mediterranean across two experimental years was only 110 mm, and the soil used in the study has a clay-loam texture (Ichir et al. 2003), which might have contributed to a dramatic decrease in the leaching risk of fertilizer N. In addition, there were still sizeable portions of the residual N (15–21%) remaining in 0–2 m soil after the third cropping season in the present study. A similar result was found by Jia et al. (2011), who reported approximately 14.5–25.7% of fertilizer N was residual in the 0–1.5 m soil layer after the third-season harvest in a winter wheat-summer maize-winter wheat rotation system. Sebilo et al. (2013) even found that 12–15% of the labeled fertilizer N was still residing in soil organic matter more than a quarter century after tracer application.

The application rate, time, and placement significantly influence the amount and distribution of residual N in soil (Chen et al. 2016; Jia et al. 2011). In the present study, although the same rate of fertilizer N was applied initially, split N applications dramatically influence the residual amount of fertilizer N in the 0–2 m soil layer after the second- and third-season harvests, as indicated by a higher residual N with N two- or three-split applications than the single N application before sowing. This result may be attributed to the lower N losses via NH_3 volatilization and N leaching with split N applications. NH_3 volatilization was the main pathway of loss from fertilizers in alkalescent soils, especially when urea was used (Bouwman et al. 2002). The better soil moisture and temperature conditions when topdressed N applied (Fig. 1) increased the activity of soil microorganism, which promoted the biological assimilation of fertilizer N, in turn reduced NH_3 volatilization and N leaching to deep layer (Rimski-Korsakov et al. 2012). Kirda et al. (2001) also reported that applying one-third or less of the total N at planting and applying the remainder at tillering can minimize leaching risks.

Excessive N input contributed to lower NRE and higher N losses (Andraski et al. 2000; Sogbedji et al. 2000), and similar results were confirmed in our study. In treatment N1, all of the fertilizer N was applied before sowing as basal N, exceeding the plant N demand greatly, resulting in a great deal of residual N remaining in the 0–0.6 m soil layer and leaching downward over time (Fig. 3a–c). A similar tendency occurred when topdressing N at the V8 stage at a rate of 135 kg ha^{-1} (60% of total fertilizer N). In addition, compared to N2, separating topdressed N into two splits (topdressed at V8 and R1) could significantly reduce the residual fertilizer N movement to deeper soil depths (Fig. 3d–f), thus promoting the uptake by subsequent crops (Table 2). Consistent with our results, Wang et al. (2016b) found that the residual N in the 0–1 m soil depth was significantly higher when applying N with three splits than when applying N with two splits. Shi et al. (2012) also reported that the residual amount of topdressed N was higher than that of basal N in the 0–0.6 m soil layer, but the inverse result was found in the 0.6–1.0 m soil layer.

Conclusions

Our findings demonstrate that a sizable portion of residual fertilizer N could be taken up by subsequent crops in a plastic-mulched maize system, with the cumulative recovery efficiency reaching 47.6–60.8% after 3 years, which indicated that the long-term fertilizer N effect should be considered when evaluating the NRE and formulating N fertilizer managements. Split N applications or delaying N application to later growth stages could increase the residual fertilizer N in upper soil layer and promote the mineralization-immobilization turnover of N, in turn contributing to residual fertilizer N utilization by subsequent crops. In addition, we confirmed that excessive N application would increase the N loss greatly, especially when exceeding the plant N demand, resulting in a lower fertilizer N recovery in soil with a single N application. In total, split N applications significantly increased the cumulative N recovery in the plant–soil system and decreased the potential losses for 3 years.

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