

Fate of nitrogen from green manure, straw, and fertilizer applied to wheat under different summer fallow management strategies in dryland

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Abstract Returning crop residues to soil is an effective approach for sustaining organic matter concentrations and increasing nutrient availability in soils. A 2-year micro-plot field experiment was conducted in dryland to determine the green manure, straw, and fertilizer nitrogen (N)-15 uptake by wheat, their residual N in soil and losses; the effect of straw application on the fate of N from green manure and vice versa was also determined, as well as the effect of crop residue additions on the fate of fertilizer N. All the micro-plots were treated with the same amount of ¹⁵N-labeled or unlabeled fertilizer. The green manure N uptake by wheat, residual N, and N loss were 22.4, 51.7, and 25.9 % of the total added green manure N over the 2-year experiment. Straw addition significantly decreased the green manure residual soil N but increased the cumulative losses. The straw N taken up by wheat, residual N in soil, and N loss were 8.3, 31.0, and 60.7 %, respectively. Green manure addition significantly decreased the straw N taken up by wheat, increased the residual soil N, and reduced the N loss. Furthermore, the fertilizer N taken up by wheat, residual N in soil, and N loss were 32.4, 32.3, and 35.2 %, respectively. Crop residue additions significantly increased the uptake of fertilizer N by wheat in the second year.

The application of inorganic N fertilizer in combination with appropriate crop residues may be an effective approach to improve the long-term fertilizer N use efficiency, soil quality, and crop yield in wheat–summer fallow rotation systems in dryland.

Keywords Green manure · Straw · Inorganic fertilizer · Nitrogen-15 · Wheat · Dryland

Introduction

China is the world's largest fertilizer consumer and accounts for 90 % of the global increase in fertilizer use since 1981 (Liu and Diamond 2005). On the North China Plain, farmers apply 325 kg N ha⁻¹ each year, which did not significantly increase winter wheat yield but did result in high greenhouse gas emissions and reactive N losses (Cui et al. 2013). Moreover, on the dryland of Northwest China, a large amount of nitrate (1065 kg N ha⁻¹) has been accumulated in the 0–3-m soil profile, at a rate of 120 kg N ha⁻¹ year⁻¹ for 17 years, and the accumulation extended deeper into the soil during the wet season (Guo et al. 2010). These negative effects are worsening and raising concerns worldwide, especially for rapidly developing countries (Chen et al. 2011; Erisman et al. 2007). Therefore, the pursuit of more sustainable pathways for increasing crop production is of global interest (Kirchmann et al. 2002).

Returning crop residues (e.g., crop straw) and green manure to the soil is an effective approach for sustaining organic matter concentrations, enhancing biological activity, improving physical properties, and increasing nutrient availability in soil (Smith et al. 1992). Green manure from legumes is widely known to provide N to soils through biological N fixation, and this can increase the soil N supply to subsequent crops and replace the addition of a part of inorganic N fertilizers (Drinkwater et al. 1998;

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López-Bellido et al. 2004; Thorup-Kristensen et al. 2003). The application of cereal straw to soil can not only improve soil physical properties, which can reduce soil erosion risks and improve soil moisture retention (Bussiere and Cellier 1994), but can also reduce the loss of excess fertilizer N through immobilization and prolong nutrient availability, thus synchronizing nutrient release with crop demands (Powlson et al. 1985). Based on these benefits, returning crop residues to farmlands has become increasingly popular throughout the world (Chen et al. 2014).

Nitrogen release from crop residues varies depending on the residues' quality (e.g., carbon-to-nitrogen ratio (C/N), lignin), which is related to their chemical composition, and this release can influence the N cycle in soil (Chivenge et al. 2011a). Crop residues with high N concentrations, low lignin and cellulose concentrations, and low C/N ratios, such as those from legumes, often result in high N mineralization. On the contrary, wheat and maize straw crop residues usually result in low N mineralization because of N immobilization in soil with negative influence on the amount of the plant available N in soil (Gentile et al. 2009; Manzoni et al. 2008; Pansu and Thuries 2003; Yanni et al. 2011). Mixed legumes and cereal crop straw residues have been successfully used to reduce N leaching, prolong nutrient availability, and synchronize nutrient release with crop demands (Kampradit et al. 2009; Schwendener et al. 2005). Based on a field experiment conducted in the UK, Ehalotis et al. (1998) found that sequential bean-residue additions resulted in a 38 % increase in residual maize N recovery in sandy soil and a 32 % increase in sandy and clay soil. Likewise, field experiments conducted in the paddy soil of Northeast Thailand revealed that the groundnut-derived ^{15}N recovery (13 %) in rice was significantly higher from a mixed retention of groundnut residues with rice straw than that (10 %) from the retention of groundnut-only residues (Kampradit et al. 2009). Limited research has been conducted to investigate the effects of the retention of combined crop residues on residual N release and uptake by the succeeding wheat crop, residual N, and N loss on a field scale, especially in dryland areas.

Dryland farming is important for China's and the world's crop production since it accounts for 51 % of the total arable land in China and 39 % of that globally. About 75 % of wheat in the world is grown in dryland. The dryland in China is mainly distributed in the northern part of the country, and approximately 40 % of this area is located on the Loess Plateau. In these dryland regions, limited precipitation and poor soil fertility are the key factors limiting crop production (Li et al. 2009; Zhang et al. 2009). Winter wheat (*Triticum aestivum* L.) summer fallow is the major cropping system. A recent report by Li et al. (2014) showed that the combination of wheat straw mulching and soybean green manure planting during the summer-fallow period mitigated the negative effects of increased soil water consumption by soybean growth and decreased the available N supply by straw mulching. Thus, this combination provided a feasible

method for summer fallow management in the dryland of the Loess Plateau in China and in similar regions of the world. Therefore, the combined retention of different crop residues from cereals and legumes may be of realistic significance for increasing the N uptake by succeeding dryland crops.

In addition, the retention of wheat straw and legume residues or their combination can change the soil N dynamics (Handayanto et al. 1997), but the fate of green manure N as affected by wheat straw addition and vice versa, as well as the fate of fertilizer N in dryland soils treated with different crop residues, are poorly understood. Therefore, tracing the fate of N derived from wheat straw, green manure, or their combination, and from fertilizer N under different crop residue addition is needed to quantify N dynamics in soil and increase fertilizer N use efficiency in dryland. Therefore, the main objectives of this study were to (i) monitor the fate of N applied through cereal straw, green manure, and fertilizer; (ii) identify the fate of green manure N affected by straw application and vice versa; and (iii) evaluate the effects of different crop residue additions on the fate of fertilizer N. To address these issues, a 2-year field experiment using ^{15}N -labeled green manure, ^{15}N -labeled wheat straw, and ^{15}N -labeled inorganic fertilizer was conducted in a wheat–summer fallow cropping system in dryland.

Material and methods

Site description

The field experiments were conducted at Shilipu in Changwu County, Shaanxi Province of China (35° 12' N, 107° 45' E), from 2008 to 2011. The experimental area has a warm temperate semi-humid continental monsoon climate with an average annual temperature of 9.1 °C, a mean precipitation of 579 mm (55 % during July–September) (Fig. 1), and a frost-free period of 171 days. The potential evaporation is 1500 mm. The Loess soil at the experimental site is classified as a Cumuli-Ustic Isohumosols (USDA soil classification system). The initial main properties of the 0–40-cm soil layer at the experimental site are presented in Table 1. The soil bulk density was between 1.32 and 1.43 g cm⁻³ in the 0–40-cm soil profiles, 1.06–1.14 g cm⁻³ in the 40–120-cm soil profiles, and 1.15–1.31 g cm⁻³ in the 120–300-cm soil profiles. A typical dryland farming system has a summer fallow (July–September), and winter wheat (*T. aestivum* L.) is annually sowed in late September or in early October and harvested in late June or in early July of the following year.

Preparation of ^{15}N -labeled green manure and wheat straw

Green manure

Nitrogen-15-labeled green manure was obtained from a widely used local soybean (*Glycine max* (L.) Merr.).

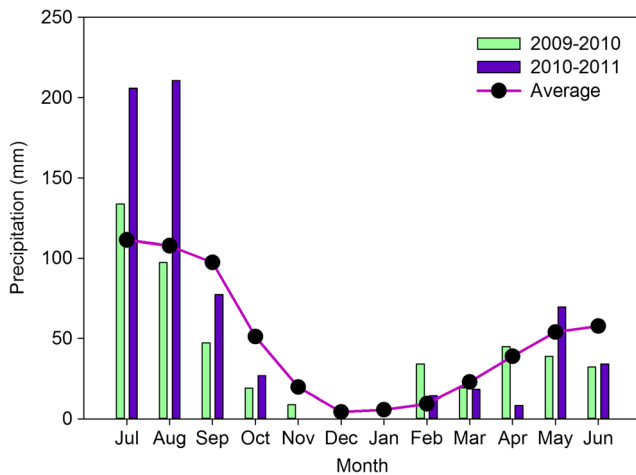


Fig. 1 Monthly precipitation (mm) from July 2009 to June 2011 and the long-term averages (1957–2012). Data are from the Changwu Agroecological Experimental Station in the Loess Plateau, Institute of Soil and Water Conservation, Chinese Academy of Sciences and Ministry of Water Resources. The average means the average precipitation of 56 years from 1957 to 2012

The cultivar “Huaidou” was grown in separated micro-plots (1×1 m) with four replicates in the experimental field during the summer fallow at seeding rate of 75 kg ha⁻¹. Nitrogen-15-labeled urea (CO (¹⁵NH₂)₂, Shanghai Institute of Chemical Industry, China) with 20.35 atom% ¹⁵N (60 kg N ha⁻¹) was applied as the basal fertilizer during the sowing of the soybean. The green manure was harvested at the flowering stage in 2009, and five plants from each micro-plot were separated into aboveground parts and roots as subsamples. After the root samples were washed with tap water to remove the attached soil and dried with a towel, the aboveground parts and roots were weighed and oven-dried at 90 °C for 30 min, and then at 70 °C to achieve a constant weight for dry weight calculations and chemical analyses. All the other fresh green manure plants were chopped into 3–5-cm segments and used as ¹⁵N-labeled green manure. The chemical properties of green manure are presented in Table 2.

Wheat straw

In late September 2008, winter wheat (*T. aestivum* L.) was sown in separated micro-plots (1×1 m) with four replicates in the experimental field at seeding rates of 150 kg ha⁻¹. The soil in the micro-plots was labeled using 10 atom% ¹⁵N of urea at a rate of 240 kg N ha⁻¹. The aboveground biomass was harvested at maturity in June 2009 and separated into ears and straw (including stems and leaves). Ten wheat straw plants from each micro-plot were separated from all the straw parts for use as subsamples. The straw was weighed and dried as described for the green manure preparation. All the other dried straw plants were chopped into 3–5-cm segments and used as ¹⁵N-labeled winter wheat straw. The chemical properties of winter wheat are presented in Table 2.

Experimental design

The field experiment consisted of macro- and micro-plot experiments. The macro-plot experiment was initiated on 23 June 2009 at the harvest of the former season’s winter wheat and lasted for two consecutive years, until 27 June 2011. The experiment included four treatments: (i) conventional practice (C), the soil was plowed 2–3 weeks after the winter wheat was harvested, and then under bare fallow conditions during the summer fallow period; (ii) straw retention (SR), the wheat straw was evenly scattered on the soil surface at harvest; (iii) green manure (GM), all wheat straw was removed from the field at harvest, and a widely used local soybean [*G. max* (L.) Merr.] cultivar “Huaidou” was seeded as a green manure crop in the summer fallow at a seeding rate of 75 kg ha⁻¹ in the first year and 150 kg ha⁻¹ in the second year (the increased seeding rate in the second year was due to the poor germination of the soybean in the first year); and (iv) straw retention + green manure (SR + GM), with combination of the SR and GM treatments. In the last three treatments, the soil was tilled at the soybean flowering stage (2–3 weeks before the next winter wheat sowing) with the wheat straw residue and chopped soybean plants incorporated into soil. The same amounts of N and phosphorus (P) fertilizers were applied in all treatments. The N fertilizer was applied as urea and at the recommended

Table 1 Main chemical properties of the 0–40-cm soil layer sampled from the long-term field experiment at seeding and before fertilizer application in 2008

Layer (cm)	Organic C (g kg ⁻¹)	Total N (g kg ⁻¹)	Available P (mg kg ⁻¹)	Available K (mg kg ⁻¹)	pH (H ₂ O)	Mineral N	
						NO ₃ ⁻ -N (mg kg ⁻¹)	NH ₄ ⁺ -N (mg kg ⁻¹)
0–10	8.73 (0.11)	0.81 (0.01)	5.4 (0.7)	139.9 (7.9)	8.18 (0.03)	13.0 (0.9)	2.9 (0.2)
10–20	8.32 (0.16)	0.73 (0.02)	3.6 (0.6)	119.4 (4.3)	8.17 (0.01)	13.2 (0.6)	2.2 (0.4)
20–40	6.28 (0.16)	0.58 (0.01)	1.6 (0.3)	122.0 (6.3)	8.24 (0.01)	8.6 (0.5)	1.8 (0.2)

Values are means (SE) (n=28)

Table 2 Nitrogen (N) and carbon (C) composition of the labeled materials

Exogenous N	Total C, % of dry matter	Total N	C to N ratio	¹⁵ N (atom%)
Fertilizer	–	46 (0)	–	19.985 (0)
Wheat straw	49.0 (1.3)	0.40 (0.01)	123 (3.9)	5.471 (0.167)
Green manure	44.8 (1.0)	2.89 (0.05)	16 (0.5)	1.029 (0.053)

Values are means (SE) ($n=4$)

rate of 138 kg N ha⁻¹ in the first experimental year, with 104 kg N ha⁻¹ applied as basal fertilizer at sowing and the rest as top-dressed fertilizer in early spring. In the second experimental year, the N rate was 150 kg N ha⁻¹, with 112 kg N ha⁻¹ applied as basal fertilizer and the rest as top-dressed fertilizer. The P fertilizer (triple superphosphate) application rate was 105 kg P₂O₅ ha⁻¹, based on tests of the available P in the soil during the two experimental years. A randomized complete block design was used, and each treatment was replicated four times. The size of each plot was 22×6 m. A widely used local cultivar of winter wheat “Changwu 521” was used and sown at 150 kg ha⁻¹ with 15-cm row spacing in late September or early October. Winter wheat was harvested in late June or early July. Detailed descriptions of the field experiment management conditions were reported by Li et al. (2014).

The ¹⁵N trace experiment was carried out in micro-plots (0.45×0.45 m) at the same time as the macro-plot experiment. The micro-plot soil was separated from the macro-plot soil by zinc-galvanized iron plates, 30 cm high of which 5 cm above-ground. To quantify the effect of green manure application on the fate of straw N, ¹⁵N-labeled wheat straw micro-plots were included in the SR (normal urea + ¹⁵N-labeled straw) and SR + GM (normal urea + ¹⁵N-labeled straw + normal green manure) treatments. Similarly, micro-plot experiments were included in the GM (normal urea + ¹⁵N-labeled green manure) and SR + GM (normal urea + normal straw + ¹⁵N-labeled green manure) treatments to monitor the fate of green manure N after the application of wheat straw. To evaluate the effect of different crop residue additions on the fate of fertilizer N, ¹⁵N-labeled fertilizer micro-plots (¹⁵N-urea, ¹⁵N-urea + normal straw, ¹⁵N-urea + normal green manure, and ¹⁵N-urea + normal straw + normal green manure) were set up in the C, SR, GM, and SR + GM treatments, respectively. For the straw micro-plots, 122 g of ¹⁵N-labeled or unlabeled dry winter wheat straw (the same amount as the average straw biomass per unit area in the macro-plots) was evenly scattered over the soil surface after planting the soybean. At the time of soybean harvest, the soybean plant was mowed and chopped into 3–5-cm segments, mixed with 15 cm of topsoil collected from the micro-plots, and then refilled into the corresponding micro-plots. For the green manure micro-plots, 180 g of ¹⁵N-labeled or unlabeled fresh green manure (the same amount as the average green manure biomass per unit area in the macro-plots) was incorporated into the field using the abovementioned topsoil refilling procedure. For the fertilizer micro-plots, ¹⁵N-labeled or unlabeled urea was applied

at the same amount and same time as that in the macro-plot. Also, in the micro-plots, the abovementioned topsoil mixing and refilling procedure was performed. Three rows of winter wheat were sown in each micro-plot at seeding rate of 150 kg ha⁻¹. For the top-dressing application in early spring, ¹⁵N-labeled or unlabeled urea was mixed with 100 g of soil removed from the corresponding micro-plot, and then evenly applied into the furrow between the wheat rows. Unlabeled fertilizer was applied in the second experimental year using the same amount as that in the macro-plots. All other management operations were consistent with those used in the macro-plots.

Sampling

Wheat

All the winter wheat plants in each micro-plot were hand-cut with scissors at the connection of the root and stem at harvest. The ears and straws from the same plots were separated for further analysis. After being air-dried, the ears were threshed, and the grains, glumes, and straws were weighed. Subsamples of 10 g for grain, 5 g for glumes, and 5 g for straws were oven-dried at 90 °C for 30 min, and then at 70 °C for 48 h for the dry-weight calculations and total N and ¹⁵N enrichment analyses. The leftover glumes and straws were returned to the original micro-plots. The sampling method for the macro-plot winter wheat was described by Li et al. (2014).

Soil

Every year, soil samples (0 to 300-cm depth in 20-cm increments) from one point between two seeding rows in each micro-plot were collected using an auger (inner diameter 4.0 cm) after wheat harvest (29 June in 2010, 28 June in 2011). After sieving (<3 mm) soils were immediately analyzed for soil moisture, mineral N (NH₄⁺-N and NO₃⁻-N) content, and ¹⁵N enrichment of the mineral N. Additional subsamples were air-dried, sieved (<2 mm), and stored prior to the determination of total N and its ¹⁵N enrichment.

Chemical analyses

The ground plant samples (0.25 g) were digested by the H₂SO₄-H₂O₂ method (Bremner and Mulvaney 1982), and the total N

in the digestate was measured with a high-resolution digital colorimeter auto-analyzer 3 (AA3, SEAL company, Germany).

The soil moisture was measured by oven drying the samples at 105 °C for 24 h. The soil mineral N was extracted from 5.0 g of fresh soil with 50 ml 1 M KCl (Henriksen and Selmer-Olsen 1970), and then measured using the high-resolution digital colorimeter auto-analyzer 3. The soil samples (1.0000 g) were sieved (<0.15 mm), digested with the H₂SO₄-mixed catalyst method (Bremmer and Mulvaney 1982), and the total N in the digestate was measured with the high-resolution digital colorimeter auto-analyzer 3.

The ¹⁵N enrichment of the mineral N of soil was determined by the diffusion method, as described by Sebilo et al. (2004). The ¹⁵N concentration in the samples was determined with a PDZ Europa 20–20 isotope ratio mass spectrometer (Sercon Ltd., Cheshire, UK) at the Stable Isotope Facility, University of California at Davis, USA, based on a 0.30‰ (δ¹⁵N) internal standard.

Calculations and data analysis

The percentage of added N (fertilizer, wheat straw, and green manure) taken up by wheat or remaining in soil (Ndff, %) was calculated according to the following equation:

$$Ndff (\%) = a/b \times 100$$

where *a* is the atom% of ¹⁵N in the plant or soil, and *b* is the atom% of ¹⁵N of the added material (fertilizer, wheat straw, or green manure).

The added N taken up by wheat was calculated as follows:

$$\begin{aligned} \text{Plant total N (kg ha}^{-1}\text{)} &= \text{plant dry matter (kg ha}^{-1}\text{)} \\ &\times \text{N content (g kg}^{-1}\text{)} / 1000 \end{aligned} \quad (1)$$

$$\text{Added N taken up by wheat (kg ha}^{-1}\text{)} = (1) \times Ndff_{\text{plant}} / 100 \quad (2)$$

$$\begin{aligned} RN_{\text{tot}} (\text{kg ha}^{-1}) &= \text{soil total N (g kg}^{-1}\text{)} \\ &\times \text{soil depth increment (cm)} \\ &\times \text{soil bulk density (g cm}^{-3}\text{)} / 10000 \\ &\times Ndff_{\text{soil}} / 100 \end{aligned} \quad (3)$$

where RN_{tot} is the residual added N present in soil.

$$\begin{aligned} RN_{\text{min}} (\text{kg ha}^{-1}) &= \text{soil mineral N (mg kg}^{-1}\text{)} \\ &\times \text{soil depth increment (cm)} \\ &\times \text{soil bulk density (g cm}^{-3}\text{)} / 10 \\ &\times Ndff_{\text{soil}} / 100 \end{aligned} \quad (4)$$

where RN_{min} is the added N present in soil mineral N.

$$RN_{\text{org}} (\text{kg ha}^{-1}) = (3) - (4)$$

where RN_{org} is the added N present in soil organic N.

$$LN (\text{kg ha}^{-1}) = \text{Total added N (kg ha}^{-1}\text{)} - (2) - (3) \quad (5)$$

where LN is the added N lost from the soil-plant system.

$$N \text{ uptake by wheat (\%)} = (2) / \text{Total added N (kg ha}^{-1}\text{)} \times 100$$

$$\text{Residual N (\%)} = (3) / \text{Total added N (kg ha}^{-1}\text{)} \times 100$$

$$N \text{ loss (\%)} = (5) / \text{Total added N (kg ha}^{-1}\text{)} \times 100$$

The statistical analysis was conducted using the SAS software package (version 9.1). Significant differences of the effects of green manure, wheat straw and fertilizer N additions on the ¹⁵N uptake by wheat, their residual N in soil, and their losses were determined using a one-way ANOVA after testing for normality. The significant differences among the measured variables between treatments were compared using the least significant difference (LSD) test at the 0.05 probability level.

Results

Wheat grain yield, aboveground biomass, and N uptake

The wheat grain yield, aboveground biomass, and N taken up by the aboveground parts in the first year showed no significant difference between the C, SR, GM, and SR + GM treatments (Table 3). Compared with the C treatment, the GM treatment decreased the grain yield by 2.2 % and the SR + GM treatment increased the grain yield by 2.4 % in the second year. Although the grain yield and the aboveground biomass in the SR treatment were not significantly different from those in the C treatment, the SR treatment reduced the N uptake by the aboveground parts by 11 % in the second year.

Fate of green manure N

The green manure N taken up by wheat over both or either of the 2 years showed no significant difference between the GM and SR + GM treatments (total N uptake of 15.4 and 14.2 kg ha⁻¹, respectively), and accounted for 22.4 and 20.6 % of the total added green manure N (Table 4). Most of the green manure N uptake by wheat occurred in the first year. However, compared with the GM treatment over the 2-year experimental period, the SR + GM treatment significantly decreased the residual added N of soil (0–300 cm) at harvest

Table 3 Wheat grain yield, aboveground biomass, and the N uptake in aboveground biomass affected by the addition of different crop residues in the 2-year field experiment

Treatments	Grain yield (Mg ha ⁻¹)		Aboveground biomass (Mg ha ⁻¹)		N uptake in aboveground biomass (kg ha ⁻¹)	
	First year	Second year	First year	Second year	First year	Second year
C	3.06 (0.23) a	5.07 (0.06) b	6.76 (0.43) a	11.17 (0.14) a	98 (5) a	156 (3) a
SR	3.15 (0.10) a	5.02 (0.06) bc	6.88 (0.15) a	11.51 (0.39) a	98 (2) a	139 (5) b
GM	2.97 (0.14) a	4.96 (0.06) c	6.68 (0.32) a	11.13 (0.17) a	96 (4) a	148 (6) ab
SR + GM	3.07 (0.23) a	5.19 (0.08) a	6.77 (0.49) a	11.26 (0.29) a	93 (5) a	157 (2) a

Values are means (SE) ($n=4$). Mean values followed by different letters in the same column indicate significant differences at $p < 0.05$

C conventional practice, SR straw retention, GM green manure, SR + GM straw retention + green manure

(16.8 % of the added green manure N) and increased the green manure N loss (i.e., unaccounted N) by 12.8 kg ha⁻¹.

The distribution of green manure N in wheat organs did not show a significant difference between the GM and SR + GM treatments (Fig. 2). In the GM treatment, the amount of green manure N was 5.7, 3.9, and 8.8 % of the total added green manure N in the stem, glume, and grain, respectively, in the first year. The corresponding percentages for the SR + GM treatment were 4.6, 2.5, and 9.3 %, respectively. In the second year, the corresponding percentages were negligible: 0.7, 0.2, and 3.1 % and 0.8, 0.2, and 3.3 % for the GM and SR + GM treatments, respectively.

After two growing seasons, the residual green manure N in soil was mainly present as organic N, with a concentration of 33.3 and 23.3 kg ha⁻¹ (48.6 and 34.0 % of the added green manure N), for the GM and SR + GM treatments, respectively. Most of organic N was found in the top 0–20-cm soil layer (37.2 and 29.8 % of the added green manure N) (Fig. 3). In contrast, the inorganic N concentration was only 2.11 and 0.64 kg ha⁻¹ (3.1 and 0.9 %) for the GM and SR + GM treatments, respectively, and was also mainly distributed in the 0–20-cm soil layer.

Fate of wheat straw N

The straw N taken up by wheat in the SR treatment accounted for 5.6 and 2.7 % of the added straw N in the first and second year, respectively (Table 5). Compared with the SR treatment, the SR + GM treatment significantly decreased the straw N taken up by wheat by 0.4 kg ha⁻¹ in the first year, whereas no significant difference between the two treatments existed in the second year. However, over the 2 years, the straw N present in soil at harvest was 3.9 kg ha⁻¹ higher in the SR + GM treatment than in the SR treatment and accounted for 16.4 % of the added straw N, and compared with the SR treatment, the SR + GM treatment decreased the straw N loss by 14.5 % of the added straw N.

In the first year, the straw N of stems and grains of wheat was significantly lower for the SR + GM treatment than for SR treatment but showed no significant effect in glumes (Fig. 4). The first-year N concentrations in the stem, glume, and grain were 2.3, 1.1, and 2.2 % of the added straw N, respectively, for the SR treatment. The corresponding percentages were 1.2, 0.8, and 1.7 % for the SR + GM treatment. In the second year, the N distribution in wheat was not significantly different between treatments.

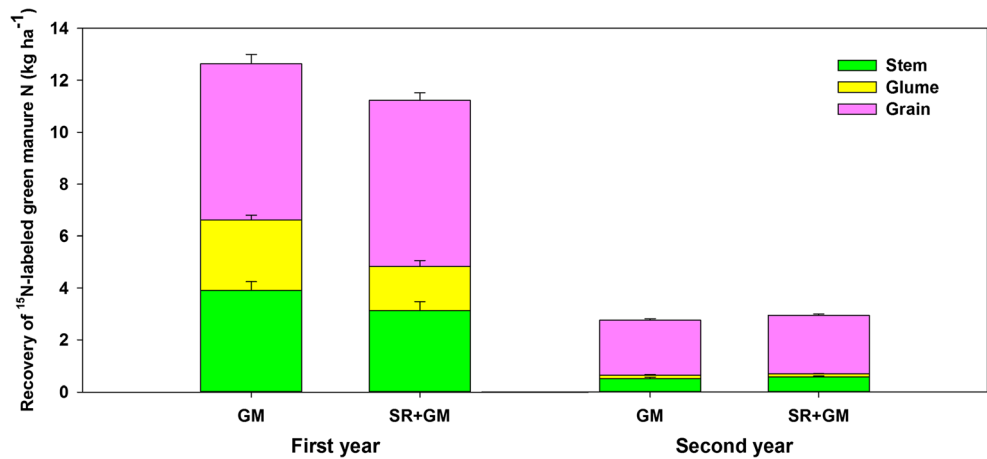
Table 4 Green manure N uptake by wheat in the aboveground parts, residual N in the 0–300-cm soil layer, and the cumulative N loss affected by straw addition over the 2-year field experiment

Treatments	N uptake by wheat (kg ha ⁻¹)			Residual N in soil after 2 years (kg ha ⁻¹)	Cumulative N loss over 2 years (kg ha ⁻¹)
	First year	Second year	Total		
GM	12.6 (0.6) a	2.8 (0.12) a	15.4 (0.5) a	35.4 (0.9) a	17.7 (1.1) b
SR + GM	11.2 (0.7) a	2.9 (0.03) a	14.2 (0.7) a	23.9 (0.2) b	30.5 (0.6) a
Ratio to the total added green manure N (%)					
GM	18.4 (0.8) a	4.0 (0.18) a	22.4 (0.7) a	51.7 (1.2) a	25.9 (1.6) b
SR + GM	16.3 (1.0) a	4.3 (0.04) a	20.6 (1.0) a	34.9 (0.3) b	44.5 (0.9) a

Values are means (SE) ($n=4$). Mean values followed by different letters in the same column indicate significant differences at $p < 0.05$. The amount of N applied by the ¹⁵N-labeled green manure was 68.5 kg ha⁻¹

GM green manure, SR + GM straw retention + green manure

Fig. 2 Green manure N taken up by winter wheat and its distribution in different organs and parts of winter wheat for the green manure (GM) treatment and the straw retention + green manure (SR + GM) treatment in the 2-year field experiment. There were no significant differences in the recovery of ¹⁵N-labeled green manure N between the GM and SR + GM treatments for the aboveground wheat parts and different organs at *p*<0.05



Similar to the residual green manure N, the residual straw N of soil was also mainly in the organic form, accounting for 30.1 and 46.6 % of the added straw N for the SR and SR + GM treatments, respectively; most of that was in the top 0–20-cm soil layer (30.0 and 45.2 %, respectively) (Fig. 5). The percentage of the added straw N present in inorganic N were 1.1 and 1.0 % for the SR and SR + GM treatments, respectively

Fate of fertilizer N

The fertilizer N taken up by wheat showed no significant difference among the C, SR, GM, and SR + GM treatments in the first year or the total of the 2 years; 32.4, 33.3, 32.1, and 33.8 % of the added fertilizer N were taken up in the C, SR, GM, and SR + GM treatments, respectively after 2 years (Table 6). However, compared with the C treatment, the SR, GM, and SR + GM treatments significantly increased the fertilizer N taken up by wheat by 24.4, 32.4, and 54.1 %, respectively, in the second year.

Different crop residue additions did not have significant effects on fertilizer N distribution in the different wheat organs in the first year (Fig. 6). In the first year, on the average of the four treatments (5.2, 2.4, and 21.9 % of the added fertilizer N) were present in the stem, glume, and grain, respectively. In the second

year, compared with the C treatment, the other three treatments significantly increased the fertilizer N of the wheat grain by 20.9, 36.0, and 60.6 %, respectively. The amount of fertilizer N of stem and glume in the second year were negligible, ranging from 0.45 to 0.57 % and from 0.11 to 0.13 % of the added fertilizer N.

Similarly, after 2 years, most of the residual fertilizer N was as organic N in the 0–20-cm soil layer (Fig. 7). The percentages of the added fertilizer N in the 0–300-cm soil layer in the organic form were 29.7, 29.4, 28.7, and 26.0 % for the C, SR, GM, and SR + GM treatments, respectively. The corresponding percentages in the 0–20-cm soil layer were 27.1, 26.1, 23.0, and 22.7 %. As it concerns of the inorganic N, the percentages of 0–300-cm soil layer were 2.6, 1.7, 2.3 and 1.6 %, and ranged from 0.5 to 1.4 % of the added fertilizer N in the 0–20-cm soil layer.

Discussion

Fate of N from green manure, straw, and fertilizer

The green manure N taken up by wheat agrees with reported values of N taken up by cereal crops (Bergstrom and Kirchmann 2004; Douxchamps et al. 2011; Janzen et al.

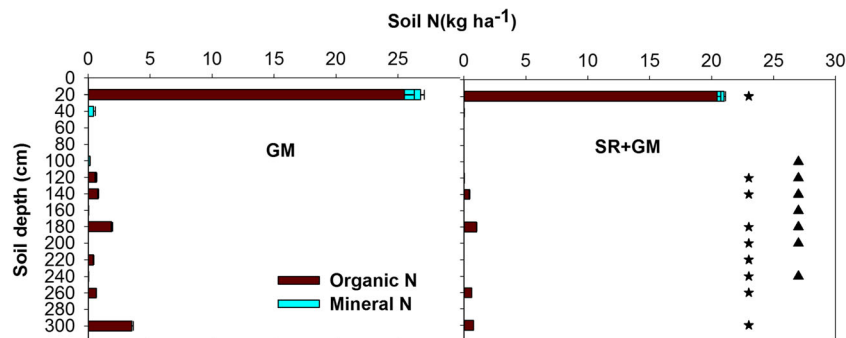


Fig. 3 Residual N from green manure as organic and inorganic N in the 0–300-cm soil profile for the green manure (GM) treatment and the straw retention + green manure (SR + GM) treatment in the 2-year field experiment; stars indicate significant differences in the amount of organic N

between the GM and SR + GM treatments at *p*<0.05; triangles indicate significant differences in the amount of inorganic N between the GM and SR + GM treatments at *p*<0.05; otherwise, there were no significant differences

Table 5 Straw N uptake by wheat in the aboveground parts, residual N in the 0–300-cm soil layer, and cumulative N loss affected by the addition of green manure over the 2-year field experiment

Treatments	N uptake by wheat (kg ha ⁻¹)			Residual N in soil after 2 years (kg ha ⁻¹)	Cumulative N loss over 2 years (kg ha ⁻¹)
	First year	Second year	Total		
SR	1.3 (0.05) a	0.7 (0.02) a	2.0 (0.03) a	7.5 (0.07) b	14.6 (0.07) a
SR + GM	0.9 (0.06) b	0.6 (0.01) a	1.6 (0.06) b	11.4 (0.12) a	11.1 (0.10) b
Ratio to the total added straw N (%)					
SR	5.6 (0.20) a	2.7 (0.10) a	8.3 (0.14) a	31.0 (0.31) b	60.7 (0.31) a
SR + GM	3.8 (0.26) b	2.6 (0.03) a	6.5 (0.27) b	47.4 (0.50) a	46.2 (0.40) b

Values are means (SE) ($n=4$). Mean values followed by different letters in the same column indicate significant differences at $p<0.05$. The amount of N applied by the ¹⁵N-labeled wheat straw was 24.1 kg ha⁻¹

SR straw retention, SR + GM straw retention + green manure

1990; Ladd and Amato 1986). Similar percentage of green manure N in soil was reported by Crews and Peoples (2005) who showed that 58 % of the ¹⁵N-labeled legume was present in soil and 24 % was lost. Janzen et al. (1990) showed that 37–72 % (mean 53 %) of applied green manure N remained in the 0–120-cm soil layer with 24–59 % in the surface layer in semiarid regions of Western Canada.

The straw N taken up by wheat was also comparable to that reported for other cereals; however, compared to previous reports, the residual soil N was lower and the N loss was greater (Glendining et al. 2001; Hart et al. 1993). The higher residual straw N found by Glendining et al. (2001) and Hart et al. (1993) may be attributed to N bio- and abiotic-immobilization in soil, whereas the lower residual straw N in soil and its increased loss in the present study should be ascribed to the straw addition method, which was scattered on the soil surface during the summer fallow, in order to prevent the loss of soil water due to evaporation. Therefore, the N released from the decomposed straw was not as available for microbial immobilization or abiotic reactions with organic

matter or fixation by clays compared with N directly incorporated into soil. Moreover, released straw N may be lost by ammonia volatilization as soil had a high pH (8.2). Thus, a better way to decrease straw N loss is to incorporate it into the soil at the time of crop harvest.

The fertilizer N taken up by wheat was similar to that (31 %) reported by Ju et al. (2009) in the North China Plain, whereas the residual soil N was lower and the N loss was greater (45.7 and 22.2 %, respectively, by Ju et al. (2009)). Similarly, a field study conducted in arid Saharan Morocco indicated that the fertilizer N taken up by wheat was 33.1 and 2.4 % in the first and second year, respectively, the residual fertilizer N in the 0–80-cm soil layer was 42.8 % of the total added N and 17.7 % was lost after two cropping seasons (Ichir et al. 2003). Liang et al. (2013) reported that the residual N from NPK fertilizer treatment was only 7 % of the mineral N in the 0–100-cm soil profile. From 12 to 15 % of labeled N from fertilizer was found soil organic N more than a quarter century after the tracer application (Sebilo et al. 2013). The lowered residual fertilizer N in soil and the increased loss found in the present study was

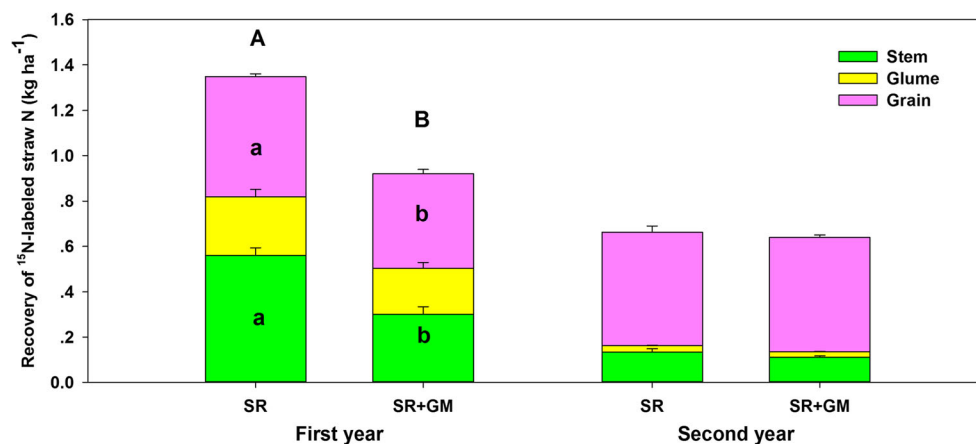


Fig. 4 Wheat straw N taken up by winter wheat and its distribution in different organs and parts of winter wheat for the straw retention (SR) treatment and the straw retention + green manure (SR + GM) treatment in the 2-year field experiment. Different uppercase and lowercase letters

indicate significant differences in the recovery of ¹⁵N-labeled wheat straw N between the SR and SR + GM treatments for the aboveground wheat parts and different organs at $p<0.05$, respectively; otherwise, there were no significant differences

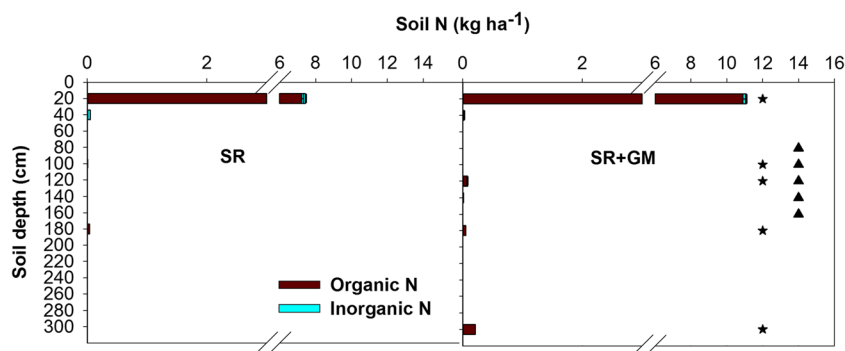


Fig. 5 Residual N from wheat straw as organic and inorganic N in the 0–300-cm soil profile for the straw retention (SR) treatment and the straw retention + green manure (SR + GM) treatment in the 2-year field experiment; stars indicate significant differences in the amount of organic N

between the SR and SR + GM treatments at $p < 0.05$; triangles indicate significant differences in the amount of inorganic N between the SR and SR + GM treatments at $p < 0.05$; otherwise there were no significant differences

probably due to the different fertilizer and water management strategies. In contrast to our experiments, both Ju et al. (2009) and Ichir et al. (2003) have irrigated soil after the N fertilizer application and this may have decreased the N loss through ammonia volatilization (Ichir et al. 2003), which probably occurred in our soil as mentioned above.

Fate of green manure N as affected by wheat straw addition and vice versa

The addition of wheat straw significantly decreased the residual green manure N in soil by 16.8 %, increased the cumulative loss by 18.5 %, but did not affect the green manure N taken up by wheat (Table 4). The result disagrees with what reported in the bibliography. According to Palm et al. (2001), green manure (soybean) is a relatively high-quality residue because it is more readily decomposable, whereas wheat straw is a relatively low-quality residue. Kampradit et al. (2009)

suggested that the mixing of groundnut residues and rice straw led to a delayed N release, which prolonged nutrient availability and led to better synchrony between nutrient release and crop N demand, and thus improved rice production. Similarly, Becker and Ladha (1997) found that the mineralization of N from a Sesbania (high-quality material)–rice straw (low-quality material) mixture was delayed compared with a Sesbania-only treatment. Myers et al. (1994) also reported that the mixing of Gliricidia residues (high quality) with rice straw resulted in a delayed N release, but the total amount of N mineralized was not altered. The different results observed in our study might be due to the fact that wheat straw was not mixed with the soybean straw during summer fallow period and the latter was incorporated into soil. Therefore, soybean N was not mixed with the poor N straw and this did not allow regulating the N mineralization of high-quality soybean residues. The mineral N released by legumes was thus available for N losses processes, such as soil

Table 6 Fertilizer N uptake by wheat in the aboveground parts, residual N in the 0–300-cm soil layer, and the cumulative N loss affected by the addition of different crop residues in the 2-year field experiment

Treatments	N taken up by wheat (kg ha ⁻¹)			Residual N in soil after 2 years (kg ha ⁻¹)	Cumulative loss over 2 years (kg ha ⁻¹)
	First year	Second year	Total		
C	41.0 (2.2) a	3.7 (0.1) d	44.7 (2.1) a	44.6 (0.7) a	48.6 (2.7) a
SR	41.5 (0.8) a	4.6 (0.2) c	46.0 (0.8) a	42.7 (0.3) b	49.3 (0.7) a
GM	39.4 (1.8) a	4.9 (0.2) b	44.3 (1.7) a	42.8 (1.4) b	50.9 (2.8) a
SR + GM	41.0 (2.1) a	5.7 (0.1) a	46.7 (2.2) a	38.0 (0.4) c	53.3 (2.1) a
Ratio to the total added fertilizer N (%)					
C	29.7 (1.6) a	2.7 (0.1) d	32.4 (1.6) a	32.3 (0.5) a	35.2 (1.9) a
SR	30.0 (0.6) a	3.3 (0.1) c	33.3 (0.6) a	31.0 (0.2) b	35.7 (0.5) a
GM	28.5 (1.3) a	3.6 (0.2) b	32.1 (1.2) a	31.0 (1.0) b	36.9 (2.0) a
SR + GM	29.7 (1.5) a	4.1 (0.1) a	33.8 (1.6) a	27.6 (0.3) c	38.6 (1.5) a

Values are means (SE) ($n=4$). Mean values followed by different letters in a column indicate significant differences at $p < 0.05$. The amount of N applied by the ¹⁵N-labeled fertilizer was 138 kg ha⁻¹

C conventional practice, SR straw retention, GM green manure, SR + GM straw retention + green manure

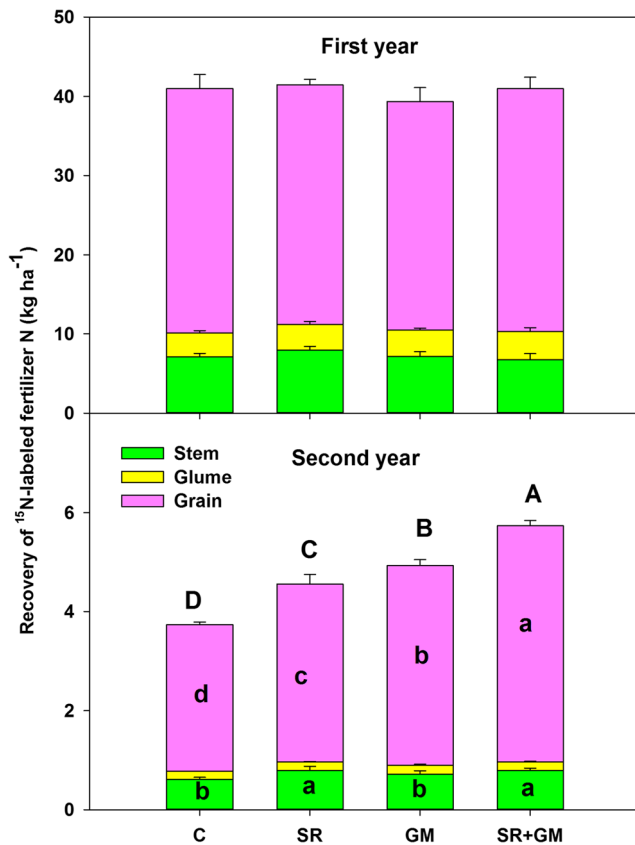
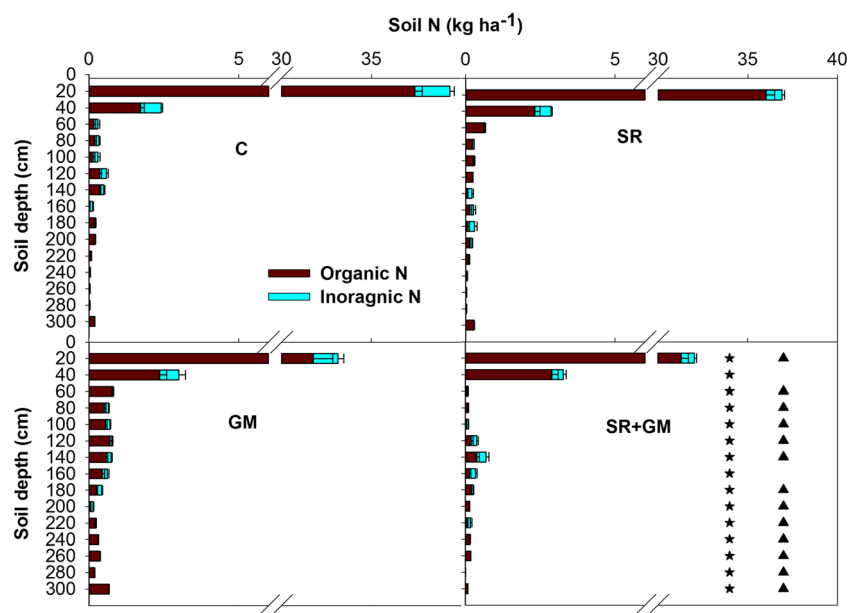


Fig. 6 Inorganic fertilizer N taken up by winter wheat and its distribution in different organs and parts of winter wheat in the conventional practice (C) treatment and treatments with different crop residues in the 2-year field experiment. Different uppercase and lowercase letters indicate significant differences in the amount of inorganic ¹⁵N fertilizer uptake by the aboveground wheat parts and different organs at $p < 0.05$, respectively; otherwise, there were no significant differences

Fig. 7 Residual N from inorganic fertilizer in the 0–300-cm soil profile as both organic and inorganic N in the conventional practice (C) treatment and treatments with different crop residues in the 2-year field experiment; stars indicate significant differences in the amount of organic N between the conventional practice (C), straw retention (SR), green manure (GM), and straw retention + green manure (SR + GM) treatments at $p < 0.05$; triangles indicate significant differences in the amount of inorganic N between the C, SR, GM, and SR + GM treatments at $p < 0.05$; otherwise, there were no significant differences



denitrification, and this may explain the decrease of the residual green manure N in soil and the increase in the cumulative N loss. Further research is needed to verify this hypothesis.

The addition of green manure significantly decreased the straw N taken up by wheat in the first year, increased the residual N in soil, and decreased the N loss (Table 5). However, Ehaliotis et al. (1998) indicated that the addition of bean plants greatly increased the recovery of N from returned maize straw in the following crops, owing to the increased microbial activity by the labile C from bean plants and then the accelerated decomposition of N from the maize residues. In the present study, the decreased straw N taken up by wheat should be caused by the different crop residue incorporation methods. When the straw was incorporated into soil with soybean plants at the end of summer fallow, the easily decomposed straw N had already been decayed, even lost as mentioned above. The remaining N was categorized as refractory compared to the fresh soybean plants. In addition, Fontaine et al. (2003) found that after the addition of fresh green manure into soil, many microorganisms preferred decomposing the fresh green manure, rather than the decomposed wheat straw.

Fate of inorganic fertilizer N as affected by crop residue additions

The addition of crop residues and green manure significantly increased the fertilizer N taken up by wheat in the second year but not in the first year (Table 6). Some studies have reported that the agronomic N use efficiency of fertilizer decreased with large additions of crop residues (Cassman et al. 2002; Ortiz Monasterio et al.

1997; Raun et al. 2002) due to the fact that the organic residues supplied more N than the N fertilizer. In contrast, other studies have reported no significant effects on fertilizer N recovery when organic residues were applied together with N fertilizers (Chivenge et al. 2011b). Organic amendments usually increase microbial activity (Blankenau et al. 2002; Edmeades 2003), and this can stimulate microbial immobilization of fertilizer or soil N (Jensen et al. 2000), decreasing the available N for crops. In the second year of this study, the increased uptake of residual fertilizer N by wheat was likely from the remineralization of the immobilized fertilizer N in the first year.

Conclusion

Our results indicated that the addition of wheat straw significantly decreased the green manure N residue in soil and increased the cumulative loss. In contrast, the combination of green manure and wheat straw treatment increased the residual straw N in soil, reduced the N loss, increased the fertilizer N taken up by wheat in the second year, and maintained the high wheat grain yields. Therefore, it is suggested that the application of N fertilizer in combination with green manure and wheat straw is an effective method to enhance fertilizer N use efficiency in the long term, with improvement of soil quality and crop yield in dryland. Further research should verify some of the hypotheses proposed here including the effect of changes in the composition of microbial communities due to the proposed treatments.

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