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Author for correspondence:
J. L. Lv,
E-mail: ljlll@nwsuaf.edu.cn

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Substituting chemical fertilizer nitrogen with organic manure and comparing their nitrogen use efficiency and winter wheat yield

Y. J. Yang[1,2], T. Lei[1,2], W. Du[1,2], C. L. Liang[1,2], H. D. Li[1,2] and J. L. Lv[1,2]

[1]College of Natural Resources and Environment, Northwest A&F University, Yangling, Shaanxi Province 712100, PR China and [2]Key Laboratory of Plant Nutrition and the Agri-environment in Northwest China, Ministry of Agriculture, Yangling, Shaanxi, PR China

Abstract

A 2-year fertilization experiment was conducted to study the effect of different ratios of organic (pig) manure on wheat yield and nitrogen use efficiency (NUE). The four treatments were no nitrogen (N) (CK); 100% chemical fertilizer N (urea; T1); 70% chemical fertilizer N + 30% organic manure N (T2) and 50% chemical fertilizer N + 50% organic manure N (T3), with the same amount of applied nitrogen (120 kg/ha). The results showed the maximum grain yield (3049 kg/ha), crop nitrogen uptake (216 kg/ha), NUE (65.4%) and accumulated nitrate nitrogen (NO_3^--N in 0–200 cm, 142 kg/ha) were observed in the T1 among all treatments in the first year. However, the largest grain yield (5074 kg/ha), crop nitrogen uptake (244 kg/ha) and NUE (82.5%) were under T2 treatment in the second year. Furthermore, T2 had the maximum NO_3^--N content in 0–100 cm layer (116 kg/ha), especially 0–40 cm layer, and the lowest NO_3^--N content in 100–200 cm (58.8 kg/ha). However, 50% organic manure N in T3 increased apparent nitrogen loss by 39.0% compared to that in T2. Therefore, 30% organic manure N application was more conducive for enhancing wheat yield and NUE and promoting environmental safety after 1-year fertilization time.

Introduction

The Loess Plateau in Northern China is a typical water-limited area that occupies an important position in wheat production. Large amounts of chemical fertilizers are usually applied to farmlands to ensure high wheat yield (Liu and Diamond, 2005, 2008). However, long-term applications of nitrogen fertilizer and improper fertilization with nitrogen (N) have been reported to cause low utilization of N fertilizer and increase the risk of groundwater through nitrate leaching (Ju *et al*., 2009; Zhou *et al*., 2016). Therefore, it is necessary to limit the application of nitrogen fertilizer and choose a reasonable method to maintain biomass and nitrogen use efficiency (NUE).

The evaluation of NUE plays an important role in understanding the application of nitrogen fertilizer and its effect on yield. Reasonable management measures are needed to increase nitrogen uptake by crops and reduce nitrogen leaching to increase NUE and optimize the application of chemical fertilizer. Nitrogen sources are crucial in regulating nitrogen transport and affecting grain yield. Substituting organic manure for chemical fertilizer is an important measure that has been widely studied to solve the problems caused by arbitrary fertilization (Xia *et al*., 2017*a*; Zhou *et al*., 2019). Many studies have shown that organic manure substitution can increase the content of soil organic matter and other nutrients, accelerate the activities of soil beneficial microorganisms, promote soil fertility and improve crop yield (Meade *et al*., 2011; Zhou *et al*., 2013; Yang *et al*., 2015). For example, Zhou *et al*. (2019) concluded that mixing organic and inorganic N fertilizer at the ratio of 1 : 1 and 2 : 1 significantly increased the vegetable yield and N uptake. Abbasi and Tahir (2012) found that replacing 25% chemical N fertilizer with organic manure could ensure stable wheat yields, promote nitrogen uptake and increase nitrogen utilization by 20%. Xia *et al*. (2017*b*) illustrated through a recent meta-analysis that substituting organic manure for chemical fertilizer increased crop productivity by 6.8%.

Studies have shown that long-term combined applications of organic manure and chemical fertilizer could effectively regulate the release of soil nitrogen, increase soil microbial biomass carbon and reduce nitrogen leaching in soil and groundwater pollution (Yadav *et al*., 2000; Qiao *et al*., 2012; Liang *et al*., 2014). Xu (1996) showed that organic manure can alleviate nitrate accumulation and leaching in the soil profile. Wen *et al*. (2016) believed that the combination of organic fertilizers could reduce the apparent nitrogen surplus and the possibility of nitrate leaching. However, improper proportions of organic manure and inorganic fertilizer do not only significantly improve biomass and water and fertilizer use efficiency, but can also cause nitrate nitrogen accumulation, which pollutes groundwater (Trewavas, 2001; Seufert et al., 2012). The average annual rainfall ranges from 300 to 600 mm, and 60% of the rainfall takes place between July and September in the Loess Plateau (Kang et al., 2003). The interannual variation of precipitation is large both spatially and temporally, and it is not consistent with the water requirements of winter wheat (Ding et al., 2015). Drought environment may inhibit the decomposition and mineralization of organic matter, thus affecting the distribution of nitrate nitrogen in soil under organic manure application.

Therefore, a 2-year field experiment was performed to evaluate how different proportions of organic manure and chemical fertilizer affect nitrogen uptake, nitrogen leaching, NUE and wheat yield. We also explored the optimum ratio of organic manure and inorganic fertilizer, which provided the basis for winter wheat production and the establishment of soil fertilization systems in this area.

Methods and materials

Experimental site and treatments

A 2-year field experiment was performed (October 2016–June 2018) in Yongshou, Shaanxi province (34°42′N and 108°09′E and is 1050 m above the sea level) on typical agricultural soil of Loess Plateau at an experimental farm of Northwest A&F university. The total precipitation was 376.7 mm in 2016 and 287.1 mm in 2017. The average maximum and minimum temperature were 15.6 and 7.8°C in the first growing season, and 16.7 and 8.4°C in the second growing season, respectively (Table 1). The experimental soil pH was 7.5 ± 0.04 and bulk density was 1.1 ± 0.02 g/cm^3. Soil organic carbon content was 14 ± 0.6 g/kg, total nitrogen was 0.8 ± 0.02 g/kg, available phosphorus was 17.5 ± 0.05 mg/kg and available potassium was 172.0 ± 0.89 mg/kg at 0–20 cm depth. Four treatments were created: 0% chemical fertilizer N (CK); 100% chemical fertilizer N (T1); 70% chemical fertilizer N + 30% organic manure N (T2) and 50% chemical fertilizer N + 50% organic manure N (T3) with the same amount of applied N (120 kg/ha). Additionally, the experiment used pig manure as manure source, and its properties include: organic carbon at 315.5 ± 0.14 g/kg, total nitrogen at 24.4 ± 0.02 g/kg and a pH of 8.2 ± 0.01. The amount of applied pig manure was 1.48 t/ha and 2.46 t/ha in T2 and T3 treatments according to the nitrogen content of pig manure, respectively. Each test plot area was 6 m × 10 m in size arranged in a randomized complete block with three replicates. Lateral protection of 0.5 m and longitudinal protection of 1 m was placed to reduce marginal effect. The N sources including chemical N fertilizer and organic manure were applied once a year in the experiment. A total of 2/3 of chemical N fertilizer (urea) and total organic manure were applied in early October before planting, and 1/3 was used as top dressing in the April. The same amount of P was applied in the field with calcium superphosphate. A total of 80 kg/ha P_2O_5 and all pig manure were incorporated into the soil in October prior to planting. Winter wheat cultivar 'Tongmai 6' was planted at a rate of 150 kg/ha seed. Crop management including sowing, harvesting, ploughing and rotating was performed according to traditional agricultural practices.

Soil and plant sample collection

Crops from each plot were harvested manually. The wheat samples from two 1 m^2 plots including grains and straws were weighted and dried to calculate the dry weights of grain yield and biomass. The moisture content of grain and straw was 11.2 and 12.5%, respectively. The total nitrogen content of crop samples was digested by H_2SO_4–H_2O_2 and examined using a Kjeldahl nitrogen analyzer. N uptake of winter wheat grains and straws were calculated via dry matter yields and N concentrations. Soil samples from 0–200 cm were collected before sowing and after harvesting using the soil-drilling method. The soil samples were then gathered 20 cm each from the 0–120 cm layer and 40 cm from the 120–200 cm layer. Soil NO_3^--N was extracted via 1 mol/l KCl and examined by automatic continuous flow analyzer (AA3, Bran + Luebbe, Germany). Bulk density was determined via the cutting ring method. NO_3^--N (mg/kg soil) was converted by NO_3^--N content and bulk density.

Statistical analysis

Only the NO_3^--N of 0–100 cm soil layer was calculated for the N balance.

N inputs = initial NO_3^--N before sowing + N mineralization + applied N from the chemical N fertilizer and organic manure

N outputs = crop N uptake + residual soil NO_3^--N + apparent N loss

N mineralization was determined by the balance of inputs and outputs in the CK in line with the following formula:

N mineralization = N uptake from the CK + initial 0–100 cm soil NO_3^--N in the CK − residual 0–100 cm soil NO_3^--N in the CK (units: kg/ha)

Harvest index (HI, %) = grain yield/biomass (above ground) × 100

N harvest index (NHI, %) = grain nitrogen uptake/crop nitrogen uptake (above ground) × 100

Nitrogen use efficiency (NUE, %) = (crop nitrogen uptake in the nitrogen application treatments − crop nitrogen uptake in the CK)/nitrogen application (120 kg/ha).

Origin 2018 was used to analyse the data. SPSS 10.0 software was used to test the significance via the LSD method ($P < 0.050$).

Results

Effect of organic manure substitution on grain yield, biomass and harvest index

The grain yield, biomass and harvest index for four treatments of winter wheat in 2016–2017 and 2017–2018 are shown in Fig. 1. The grain yield and biomass in all fertilization treatments were 2621–3049 and 5490–6211 kg/ha in 2016–2017, and 4200–5074 and 8506–10 205 kg/ha in 2017–2018, respectively, while the grain yield and biomass under the CK were 2387 and 4895 kg/ha in 2016–2017 and 3412 and 7012 kg/ha in 2017–2018, respectively. In 2017–2018, the grain yield and biomass significantly increased by 15.3 and 19.9% in T2, and significantly increased by 11.2 and 17.1% in T3 compared to T1. Furthermore, the maximum harvest was in T2, but the harvest index decreased in T3 compared to T1.

Effect of organic manure substitution on nitrogen uptake and nitrogen use efficiency

The grain nitrogen uptake, crop nitrogen uptake and NUE index are shown in Table 2. In 2016–2017, the largest nitrogen uptake of grain and crop, NUE and NHI were observed in T1 with the application of chemical fertilizer, while lower values were in treatments substituted with organic manure; these changes were consistent with grain yield and biomass. In 2017–2018, the nitrogen uptake, NUE and NHI increased with substituted organic manure

Table 1. Distribution of precipitation, average maximum temperature and average minimum temperature in the experimental area during the two growing seasons (2016–2017 and 2017–2018)

Year	Growing period	Duration	Precipitation (mm)	Average minimum temperature (°C)	Average maximum temperature (°C)
2016–2017	Seedling	24	78.2	9	15
	Overwintering	46	39.9	2	10
	Jointing	99	37.6	−1.5	5.8
	Booting	76	108	12.8	19.8
	Maturity	27	113	16.7	27.3
	Average	–	75.3	–	–
	Total	272	377	–	–
2017–2018	Seedling	35	29.2	12	16.5
	Overwintering	40	56.2	2.4	8.3
	Jointing	106	51.3	−1.7	7.7
	Booting	66	87.6	11.5	22
	Maturity	27	62.8	18	29
	Average	–	57.4	–	–
	Total	274	287	–	–

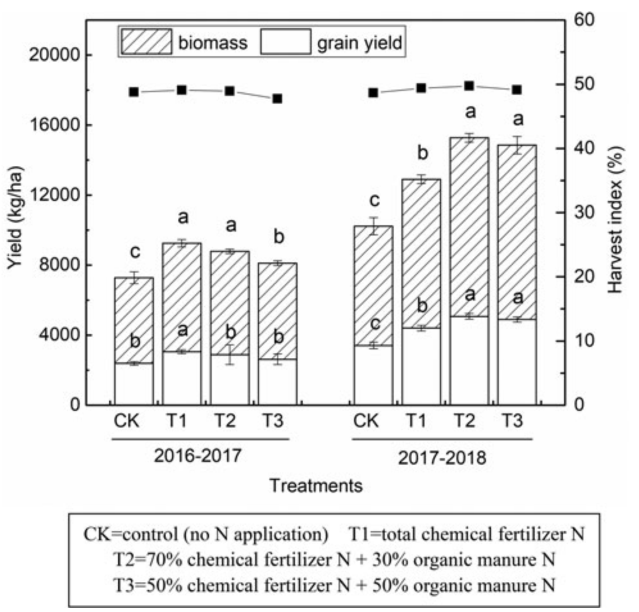

Fig. 1. Biomass, grain yield and harvest index of winter wheat in 2016–2017 and 2017–2018 among four treatments (values in each column followed by the same letter are not significantly different at $P \leq 0.05$).

compared to chemical fertilizer. Compared to T1, the grain nitrogen uptake increased by 13.9 and 2.11%, the crop nitrogen uptake increased by 3.43 and 0.25%, the NUE increased by 10.1 and 1.86% and the NHI increased by 8.88 and 0.64% in T2 and T3 treatments, respectively.

Effect of organic manure substitution on nitrate nitrogen accumulation

As shown in Fig. 2, the NO_3^--N content in 0–200 cm soil layer after wheat harvest in two seasons was significantly higher than CK. In 2016–2017, the nitrogen fertilization treatments increased the accumulation of NO_3^--N in the 0–100 cm soil layer but decreased the content of NO_3^--N in the 100–200 cm soil layer. The maximum content of NO_3^--N in 0–100 cm soil layer was observed in T2 and the NO_3^--N content decreased with the increase of substituted organic manure. In 2017–2018, compared with T1, the accumulated NO_3^--N in 0–100 cm soil layer increased in T2 and T3. Conversely, the NO_3^--N content reduced in the 100–200 cm soil layer in T2 and T3. The distribution of NO_3^--N in the different layers of 0–100 cm in the two growing seasons is shown in Fig. 2. The results showed a downward trend in the NO_3^--N content in two seasons with an increased soil depth. Compared with T1, the NO_3^--N content in 0–40 cm soil layer increased with the organic manure substitution in 2016–2017 but was not significant. However, in 2017–2018, the NO_3^--N content increased in each layer of 0–100 cm in T2 and T3, especially in the 0–40 cm soil layer.

Effect of organic manure substitution on nitrogen balance

The balance of nitrogen in different treatments is shown in Table 3. The sum of residual and mineralized NO_3^--N in 0–100 cm soil layer was insufficient for the crop. From the perspective of nitrogen outputs, the nitrogen uptake of crops increased by 15.2 and 30.2% in T1 compared with T2 and T3 in 2016–2017. Meanwhile, the maximum residual NO_3^--N in 0–100 cm soil layer was also observed in T1. Additionally, the nitrogen uptake of crops and the residual NO_3^--N of 0–100 cm soil layer in T2 increased by 13.1 and 5.17% compared with T3. The maximum apparent nitrogen loss was observed in T3. In 2017–2018, the maximum nitrogen uptake and accumulation of NO_3^--N in 0–100 cm soil layer and the minimum apparent nitrogen loss was observed in T2. However, the lowest nitrogen uptake of crops and the largest apparent nitrogen loss were observed in T1 that only has chemical fertilizer applied. Furthermore, the 30% organic manure substitute promoted crop nitrogen uptake and decreased the apparent nitrogen loss by 40.4 and 28.1% compared to

Table 2. Effect of different fertilization practices on N uptake and NUE) of winter wheat

Years	Treatments[a]	Grain N uptake (kg/ha)	Crop N uptake (kg/ha)	NUE (%)	NHI (%)
2016–2017	CK	43.3c	138b	–	31.5
	T1	75.5a	216a	65.4	34.9
	T2	63.9b	188a	41.7	34.1
	T3	57.0b	166b	23.6	34.3
2017–2018	CK	43.8b	145b	–	30.2
	T1	75.9c	236a	75.7	32.2
	T2	86.5a	244a	82.5	35.4
	T3	77.5c	237a	76.2	32.8

Values in each column followed by the same letter are not significantly different at $P \leq 0.050$.
[a]CK: control; T1: total chemical nitrogen fertilizer; T2: 70% chemical fertilizer N + 30% organic manure N; T3: 50% chemical fertilizer N + 50% organic manure N; N: nitrogen.

treatments with chemical fertilization and 50% organic manure substitution, respectively.

Discussion

Previous studies have shown that organic and inorganic fertilizers can significantly increase the yield of winter wheat (Fan *et al*., 2005; Urkurkar *et al*., 2010; Liu *et al*., 2013; Chauhan and Bhatnagar, 2014). In this study, substitution with organic manure decreased the yield of winter wheat in the first growing season. The main reason was a lack of available N in soil. The available N has been rapidly mineralized for crops by chemical fertilizer. Most of the nitrogen in organic manure exists in organic form. The release rate of available N from organic nitrogen is very slow, which was related to soil fertility, climatic conditions and other factors (Chow *et al*., 2006; Bertrand *et al*., 2007). Besides, the organic manure had difficulty in supplying nutrients for the crop and decomposed with the lower precipitation in 2016–2017. Therefore, it usually fails to meet the nitrogen demand of crops in time, thus resulting in decreased yield. Then the organic manure was gradually decomposed and mineralized more nutrients such as N and P since the increased rainfall and extension of fertilization period. The organic manure substitution enhanced the yield in the second growing season. Furthermore, the 50% organic manure substitution lowered the yield compared to 30% substituted organic manure, which was similar to the previous studies. Xin *et al*. (2017) reported that 50% substituted organic manure lowered the yield of wheat compared with the mineral fertilizer treatment. The possible explanation was the available N was insufficient in the treatment with 50% organic manure substitution.

Furthermore, the content of NH_4^+-N in dryland soil was low, mainly due to the strong nitrification of dryland soil; the mineralized NH_4^+-N was quickly converted into NO_3^--N, and NH_4^+-N was easily adsorbed by soil colloids (Wang *et al*., 2013). Therefore, in this study, it mainly focused on the distribution of NO_3^--N in dryland soil. Unreasonable input of chemical nitrogen fertilizer can result in a large NO_3^--N accumulation and leaching in soil profile (Xing and Zhu, 2000; Zhou *et al*., 2016). Promoting the utilization of NO_3^--N during wheat growth is an effective measure to reduce nitrogen application and increase NUE. The root system is the main organ plants use to absorb water and nutrients. Therefore, the NO_3^--N in 0–100 cm soil layer is the main nitrogen absorbed and utilized by wheat (Ju *et al*., 2002), which was mainly because the well-developed roots of wheat can penetrate the soil and reach about 100 cm. The observation that state that accumulated NO_3^--N in soil profiles can be effectively utilized by wheat has attracted more attention (Kristensen and Thorup-kristensen, 2004; Christiansen *et al*., 2006). In this study, the NO_3^--N content in 0–100 cm soil layer was used to conduct crop nitrogen uptake and nitrogen balance. The results demonstrated that the combined application of organic and chemical fertilizer could improve the NUE of wheat and increase the NO_3^--N content in 0–100 cm soil layer. Therefore, the absorption and utilization of available nitrogen by the crop was promoted with organic manure. This study further proves that the reasonable application of organic manure to promotes wheat roots to fully absorb NO_3^--N accumulated in soil profiles, which is an effective way to increase NUE and reduce the leaching of NO_3^--N. Furthermore, these comprehensive factors affected the increase of the yield with substituted organic manure. This was related to organic manure that contains bioactive substances that could increase the availability of nutrients and stimulate crop nutrient uptake and growth (Ai *et al*., 2012; Demelash *et al*., 2014).

Different fertilization treatments changed the residual accumulation of NO_3^--N in the soil and the distribution of NO_3^--N in soil layer. Li *et al*. (2013) suggested that the application of organic manure significantly increased total nitrogen and NO_3^--N content, and 8% of NO_3^--N came from the transformation of organic manure via N labelling experiment. In this study, the accumulation of NO_3^--N in 0–100 cm, especially the 0–40 cm soil layer in the treatment with organic manure was higher than the chemical fertilizer treatment, opposite to the results from the deeper soil layer. The results indicated organic manure substitution was more effective at decreasing the leaching of NO_3^--N to deep soil, thus avoiding the environmental pollution, which was consistent with Yin *et al*. (2007). It was concluded that combined application of organic manure and chemical fertilizer could fix NO_3^--N and prevent migration to deep soil. The possible explanation was the organic manure substitution could increase the content of soil active organic carbon and cation exchange capacity to fix NO_3^--N (Su *et al*., 2006).

In this study, the largest crop nitrogen uptake and residual NO_3^--N in 0–100 cm soil layer were observed in the treatment with chemical fertilizer in 2016–2017. The findings demonstrated

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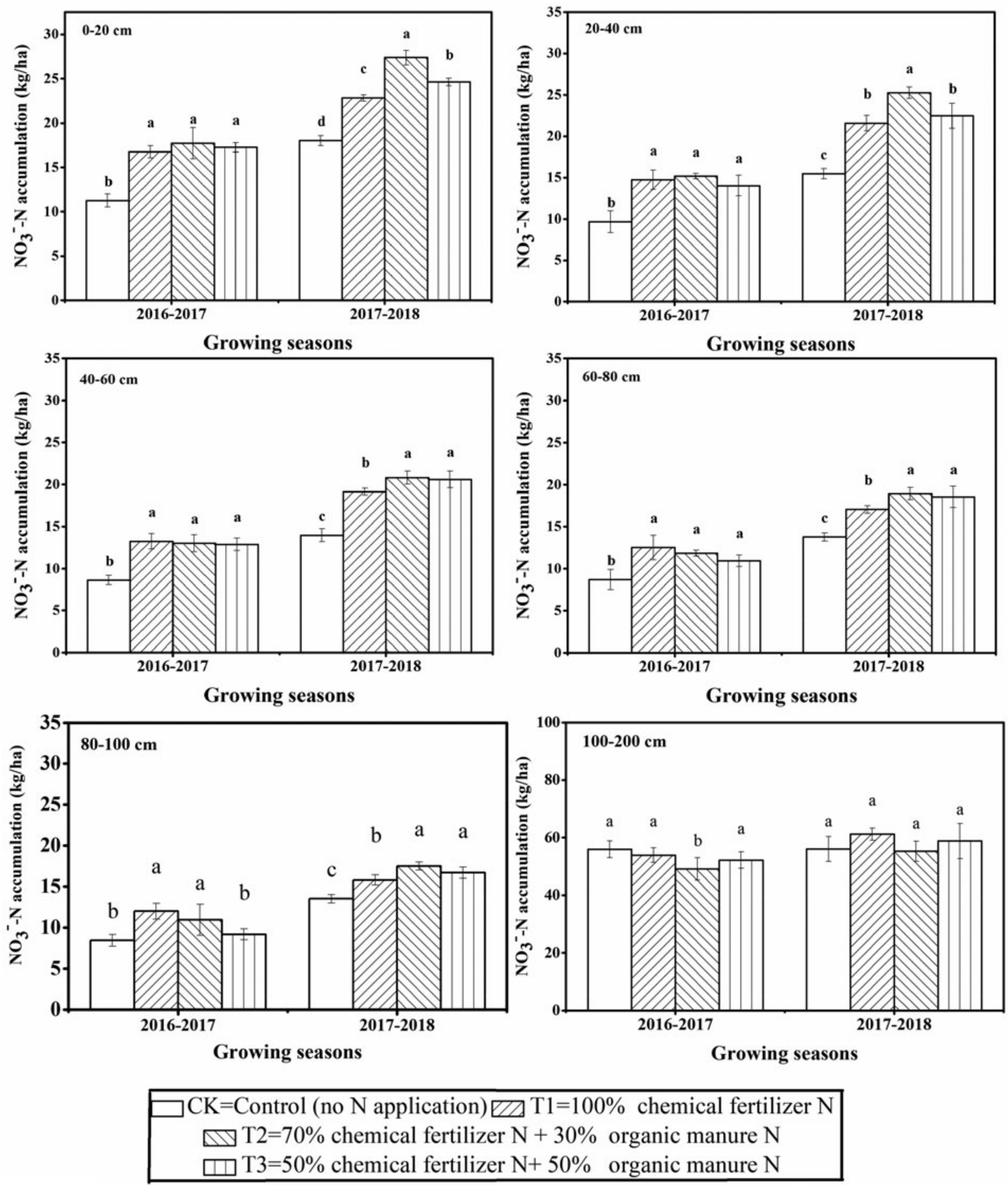

Fig. 2. Dynamic of NO_3^--N in the soil layer (0–200 cm) in 2016–2017 and 2017–2018 among four treatments (values in each column followed by the same letter are not significantly different at $P \leq 0.05$).

that chemical fertilizers are quick and efficient to use, but have lower stability, so it is difficult to meet the continuous nutrient requirement of crops. Applying organic manure could promote microbial immobilization of nitrogen when applied (Liu *et al*., 2009), so that more nitrogen is immobilized by microorganisms during the prophase of crop growth. Then, nitrogen would be gradually released via the death of microorganisms (Azeez and Van Averbeke, 2010), which follows the demand for nitrogen in the process of crop growth, thus reducing nitrogen loss and improving NUE. The results showed that the residual inorganic nitrogen in the soil was higher, and the loss of nitrogen was lower with the organic manure substitution, especially in the treatment with 30% organic manure substitution. It indicated that organic manure substitution with an appropriate proportion could promote the absorption and utilization of nitrogen and reduce the loss of NO_3^--N and environmental pollution.

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Table 3. Nitrogen balance of different fertilization treatments in two planting years

Years	Treatments[a]	N uptakes		N outputs		
		Initial N mineralization[b] (kg/ha)	N mineralization (kg/ha)	Crop N uptake (kg/ha)	Residual N mineralization[b] (kg/ha)	Apparent N loss (kg/ha)
2016–2017	CK	89.2a	117	138b	68.2b	0
	T1	80.2b	117	216a	82.4a	18.3
	T2	78.1b	117	188a	87.2a	39.9
	T3	72.5b	117	166b	82.9a	60.3
2017–2018	CK	37.9b	182	145b	74.7b	0
	T1	62.4a	182	236a	96.4a	31.9
	T2	71.1a	182	244a	110a	19.0
	T3	64.0a	182	237a	103a	26.5

Values in each column followed by the same letter are not significantly different at $P \leq 0.050$.
[a]CK: control; T1: total chemical nitrogen fertilizer; T2: 70% chemical fertilizer N + 30% organic manure N; T3: 50% chemical fertilizer N + 50% organic manure N.
[b]N: nitrogen; initial N mineralization: initial NO_3^--N content accumulated in the 0–100 cm soil layer before sowing; residual N mineralization: residual NO_3^--N mineralized in the 0–100 cm soil layer after harvesting.

Conclusion

The results of the 2-year field experiment showed that substituting 30% of the fertilizer with organic manure could promote nitrogen uptake and yield of winter wheat, thus improving NUE compared to applying chemical fertilizer alone after 1-year fertilization time. Additionally, 30% organic manure substitution increased the NO_3^--N content in in 0–100 cm, especially in 0–40 cm soil layer, but reduced the risk of NO_3^--N leaching. Considering wheat yield, NUE and environmental effects; 30% organic manure substitution was the most optimum under the application of 120 kg/ha N. But more research via long-term field experiments is still necessary.

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Conflict of interest. The authors declare there are no conflicts of interest.

Ethical standards. Not applicable.

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