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REVIEW

Nitrogen cycling and environmental impacts in upland agricultural soils in North China: A review

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Abstract

The upland agricultural soils in North China are distributed north of a line between the Kunlun Mountains, the Qinling Mountains and the Huaihe River. They occur in arid, semi-arid and semi-humid regions and crop production often depends on rain-fed or irrigation to supplement rainfall. This paper summarizes the characteristics of gross nitrogen (N) transformation, the fate of N fertilizer and soil N as well as the N loss pathway, and makes suggestions for proper N management in the region. The soils of the region are characterized by strong N mineralization and nitrification, and weak immobilization and denitrification ability, which lead to the production and accumulation of nitrate in the soil profile. Large amounts of accumulated nitrate have been observed in the vadose-zone in soils due to excess N fertilization in the past three decades, and this nitrate is subject to occasional leaching which leads to groundwater nitrate contamination. Under farmer's conventional high N fertilization practice in the winter wheat-summer maize rotation system (N application rate was approximately 600 kg ha^{-1} yr^{-1}), crop N uptake, soil residual N, NH_3 volatilization, NO_3^- leaching, and denitrification loss accounted for around 27, 30, 23, 18 and 2% of the applied fertilizer N, respectively. NH_3 volatilization and NO_3^- leaching were the most important N loss pathways while soil residual N was an important fate of N fertilizer for replenishing soil N depletion from crop production. The upland agricultural soils in North China are a large source of N_2O and total emissions in this region make up a large proportion (approximately 54%) of Chinese cropland N_2O emissions. The "non-coupled strong ammonia oxidation" process is an important mechanism of N_2O production. Slowing down ammonia oxidation after ammonium-N fertilizer or urea application and avoiding transient high soil NH_4^+ concentrations are key measures for reducing N_2O emissions in this region. Further N management should aim to minimize N losses from crop and livestock production, and increase the recycling of manure and straw back to cropland. We also recommend adoption of the 4R (Right soure, Right rate, Right time, Right place) fertilization techniques to realize proper N fertilizer management, and improving application methods or modifying fertilizer types to reduce NH_3 volatilization, improving water management to reduce NO_3^- leaching, and controlling the strong ammonia oxidation process to abate N_2O emission. Future research should focus on the study of the trade-off effects among different N loss pathways under different N application methods or fertilizer products.

Keywords: N transformation, NH_3 volatilization, ammonia oxidation, NO_3^- leaching, N_2O emission, upland agricultural soils

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1. Introduction

Upland agricultural soils in North China are distributed north of a line between the Kunlun Mountains, the Qinling Mountains and the Huaihe River. They cover 965 counties (or cities) in 16 provinces, municipalities or autonomous regions, and account for 56 and 51% of land and arable land area in China, respectively. They occur in arid, semi-arid and semi-humid regions and crop production often depends on rain-fed or irrigation to supplement rainfall. Annual precipitation ranges from 0 to 600 mm, with 50–70% occurring in summer as high intensity storms which results in frequent drying-rewetting cycles. The annual average sunshine hours range from 2 800–3 000 h, and annual accumulated temperature (>10°C) ranges from 2 500–3 500°C. These climatic conditions provide favorable conditions for crop production, especially in wet and hot summer season (Li 2004; Zhang 2016). Three major sub-regions, based on differences among soil properties, precipitation and agricultural management practices are recognized within the region. These are the Huanghuaihai Plain (also called North China Plain), the Northeast Plain, and the Loess Plateau (Liu and Chen 2005).

The soils of the North China region are characterized by low organic carbon (C) concentrations and high pH. Soil nitrogen (N) transformation is characterized by strong mineralization and nitrification, but weak immobilization and denitrification ability (Wan *et al*. 2009; Zhang *et al*. 2012; Hartmann *et al*. 2014; Zhou J Y *et al*. 2016). Although soil N transformation and loss pathways are generally similar across the region, some differences in N cycling between the various sub-regions occur. Systematic study of these similarities and differences has important theoretical and practical significance for N management and N loss reduction in the North China region.

2. Gross soil N transformation

Understanding the characteristics of soil N transformation is fundamental for better N management and reducing N losses from crop production. Most studies of N transformation have been made using measurements of net rates of N turnover; however, the ^{15}N pool dilution technique (Murphy *et al*. 2003) together with numerical models have been used to calculate gross N transformation rates and this approach has become increasingly important (Mary *et al*. 1998; Müller *et al*. 2004). It is proved to be an effective tool for revealing relationships between N mineralization and immobilization, N turnover and N loss, and N forms and availability to plants (Murphy *et al*. 2003; Zhang *et al*. 2012, 2013).

In comparison with other soils, gross N transformation of Fluvo-aquic soils in the North China Plain is characterized by Table 1: (1) high mineralization rate, about 7 kg of organic N could be transformed to mineral N per hectare per day (Wan *et al*. 2009; Zhang *et al*. 2012); (2) strong nitrification rate, which may lead to production and accumulation of nitrate in the soil profile; about 41 kg of ammonium could be transformed to nitrate per hectare per day under favorable water and temperature conditions (Wan *et al*. 2009; Zhang *et al*. 2012); and (3) high gross nitrification rate in relation to gross immobilization rate, which may lead to a high risk of NO_3^- leaching. The above characteristics contribute to the low organic N pool and high NO_3^- pool in these soils. The soil organic N pool can be improved by increasing C input and promoting the interaction between C and N (Qiu *et al*. 2013, 2015).

3. Fate of fertilizer N and soil N

Synthetic N fertilizer is only one of the various sources of N for cropping systems; other sources include manure, biological N fixation, and N deposition. With the rapid development of the N fertilizer industry, farmers have

Table 1 Gross N transformation of upland agricultural soils in North China as compared to other soils

Region (land use)	Site	Soil type[1)]	pH	Soil organic carbon (g kg^{-1})	Total nitrogen (g kg^{-1})	Gross N transformation rate (mg N kg^{-1} d^{-1})[2)]			Reference
						M	N	I	
North China (upland)	Haidian, Beijing	Fluvo-aquic soil	8.0	13.9	1.2	1.8	19.5	–	Wan *et al.* (2009)
	Fengqiu, Henan	Fluvo-aquic soil	8.4	5.6	0.7	4.3	17.1	8.5	Zhang *et al.* (2012)
	Hailun, Heilongjiang	Black soil	5.8	23.3	2.2	1.7	4.2	1.3	Lang *et al.* (2016)
South China (upland)	Yanting, Sichuan	Purple soil	7.8	7.5	0.8	8.3	23.5	7.6	Wang *et al.* (2015)
Sourth China (paddy field)	Fuzhou, Fujian	Paddy soil	5.1	13.9	1.5	2.2	1.3	0.8	Zhang Y S *et al.* (2015)
North China (temperate grassland)	27 subsites of the region	Grassland soil	8.1	15.5	1.5	3.0	3.3	1.6	Wang J *et al.* (2016)
North China (temperate forest)	5 typical subsites of the region	Forest soil	5.6	50.5	4.2	1.8	1.3	0.6	Zhang *et al.* (2013)
South China (subtropical forest)	4 typical subsites of the region	Forest soil	4.5	31.9	1.6	3.0	0.8	2.5	Zhang *et al.* (2013)

[1)] The soil is classified according to Chinese Soil Genetic Classification (Gong *et al*. 2007).
[2)] M, gross mineralization rate; N, gross nitrification rate; I, gross immobilization rate.