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Mechanisms of soil N dynamics following long-term application of organic fertilizers to subtropical rain-fed purple soil in China

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ABSTRACT

In this study, a ^{15}N tracing incubation experiment and an *in situ* monitoring study were combined to investigate the effects of different N fertilizer regimes on the mechanisms of soil N dynamics from a long-term repeated N application experiment. The field study was initiated in 2003 under a wheat-maize rotation system in the subtropical rain-fed purple soil region of China. The experiment included six fertilization treatments applied on an equivalent N basis (280 kg N ha^{-1}), except for the residue only treatment which received 112 kg N ha^{-1}: (1) UC, unfertilized control; (2) NPK, mineral fertilizer NPK; (3) OM, pig manure; (4) OM-NPK, pig manure (40% of applied N) with mineral NPK (60% of applied N); (5) RSD, crop straw; (6) RSD-NPK, crop straw (40% of applied N) with mineral NPK (60% of applied N). The results showed that long-term repeated applications of mineral or organic N fertilizer significantly stimulated soil gross N mineralization rates, which was associated with enhanced soil C and N contents following the application of N fertilizer. The crop N offtake and yield were positively correlated with gross mineralization. Gross autotrophic nitrification rates were enhanced by approximately 2.5-fold in the NPK, OM, OM-NPK, and RSD-NPK treatments, and to a lesser extent by RSD application, compared to the UC. A significant positive relationship between gross nitrification rates and cumulative N loss via interflow and runoff indicated that the mechanisms responsible for increasing N loss following long-term applications of N fertilizer were governed by the nitrification dynamics. Organic fertilizers stimulated gross ammonium (NH_4^+) immobilization rates and caused a strong competition with nitrifiers for NH_4^+, thus preventing a build-up of nitrate (NO_3^-). Overall, in this study, we found that partial or complete substitution of NPK fertilizers with organic fertilizers can reduce N losses and maintain high crop production, except for the treatment involving application of RSD alone. Therefore, based on the N transformation dynamics observed in this study, organic fertilizers in combination with mineral fertilizer applications (i.e. OM, OM-NPK, and RSD-NPK treatments) are recommended for crop production in the subtropical rain-fed purple soils in China.

1. Introduction

Soils occurring in humid subtropical regions are generally acidic and highly weathered (Bennema et al., 1970; Zhang et al., 2011). Previous investigations have demonstrated that the rates of NH_4^+ oxidation and NH_3 volatilization in these soils are low, and that NH_4^+-N is the predominant form of inorganic N (Zhang et al., 2013a,b). Thus, soil N can potentially be retained effectively, even under humid climatic conditions (Zhang et al., 2013a,b). An important arable cropping region in the humid subtropical region in China, encompassing approximately 300,000 km^2, is located in the Sichuan Basin (Li et al., 1991). In contrast to the soils normally occurring in these regions, the purple soils, classified as Eutric Regosols (Wang and Zhu, 2011), are characterized by a neutral or

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alkaline reaction, and therefore may promote NH_3 volatilization and autotrophic nitrification (Zhang et al., 2011, 2013). Nitrate is the predominant form of inorganic N in these purple soils (Wang et al., 2012; Zhu et al., 2012). Rain-fed purple soils on sloping areas cover approximately 65% of the total cropland in that region (Zhu et al., 2012). Therefore, these soils are prone to erosion and leaching due to intensive cultivation and N losses that occur through leaching and runoff, resulting in local and widespread N pollution in these regions (Huang et al., 1998; Zhu et al., 2009; Wang and Zhu, 2011). Soil and water conservation measures have been carried out to reduce overland flow and interflow N loss via, for instance, terraced tillage, ridge-furrow cropping, contour farming, and fertilizer management. Traditionally, organic manure from pig slurry has been widely used to maintain soil fertility. However, due to the wide availability of mineral fertilizers, applications of synthetic NPK fertilizers, either alone or in combination with organic fertilizers (including manure and crop residue) are now very common (Dong et al., 2014). To identify the effects of organic and mineral fertilizers on soil N retention, crop yield, and N losses, a long-term repeated N application experiment was established in 2003 (Dong et al., 2014). Soil organic N and mineral N contents, crop yield, and N losses via leaching and N_2O emissions from soils differed among the treatments (Wang and Zhu, 2011; Wang et al., 2012). For example, substitution partially organic fertilizers (either livestock manure or crop straw) for mineral fertilizers could increase crop yields and simultaneously reduce interflow N loss (Wang et al., 2012). However, the mechanisms underlying the effects of N application treatments on crop yield and N losses are not well understood.

Soil N mineralization-immobilization turnover (MIT) governs soil N availability and N conservation (Murphy et al., 2003; Huygens et al., 2007, 2008). The most common approach to gain insights into the dynamics of MIT is via ^{15}N tracing techniques which are able to identify individual N turnover processes (Müller et al., 2007; Huygens et al., 2008), and are therefore preferred over net N transformation studies (Rennenberg et al., 2009). Recently, ^{15}N tracing techniques have been used to successfully identify potential changes in N dynamics under different long-term N fertilizer management regimes (Müller et al., 2011; Zhang et al., 2012a). The concomitant increase in heterotrophic nitrification and NH_4^+ oxidation with increasing slurry application rates was mainly responsible for increased N availability in the long-term (Müller et al., 2011). Through a long-term, repeated mineral and organic fertilizer application experiment initiated in 1989, Zhang et al. (2012a) found that NO_3^- production was positively correlated with gross mineralization and inversely related to NH_4^+ immobilization. Increased net NO_3^- production is associated with N losses through NO_3^- leaching and gaseous N emission, and thus tends to reduce soil N retention. However, such studies did not elucidate the relationship between N cycling and N loss under different N management regimes, and thus, the potential mechanisms behind N losses remain unresolved. To elucidate the relationships among N retention and N loss processes under long-term applications of different fertilizers, a combination of the ^{15}N tracing technique with *in situ* monitoring are recommended (Huygens et al., 2008).

We hypothesized that long-term N application could affect the soil N transformation rates/dynamic and, in turn, control the form of soil mineral N and N losses from soils. Thus, investigations into gross N transformation rates in the different long-term N application experiments should enable an understanding of the effects of N application treatments on soil N dynamics. The objectives of this study were: (1) to investigate the effects of long-term N fertilizer management on soil-specific gross N transformation rates based on a laboratory ^{15}N tracing study, (2) to evaluate the effects of long-term application of different N fertilizer types on NO_3^- leaching and N_2O emission and crop production from various field plots, and (3) to identify the mechanisms involved in N losses and crop yields in purple soil under different N fertilization regimes. The results will be used to recommend suitable N management practices to mitigate N losses from purple soil in the subtropical rain-fed wheat–maize rotation system in the Sichuan Basin, and should also provide insight for the management of similar soils in other regions of the world.

2. Materials and methods

2.1. Site description and long-term fertilization experiment design

The field experiment was located in the Yanting Agro-Ecological Station of Purple Soil, a member station of the Chinese Ecosystem Research Network (CERN), Chinese Academy of Sciences, in the center of Sichuan Province in southwestern China (N31°16′, E105°28′) (Fig. 1). The site is characterized by a moderate subtropical monsoon climate, with annual precipitation of 1157 mm (in 2013), of which approximately 90% occurs during the summer maize growing season from May to September, and an annual average air temperature of 17.3 °C. The experimental soil is called purple soil locally because of its "purplish" color and classified as Pup-Orthic Entisols in the Chinese soil taxonomy and Eutric Regosols in FAO soil classification.

The long-term experiment initiated in 2003 was established as a randomised block design that included six treatments (fertilization treatments applied on an equivalent N basis) with three replicate plots (size: 6 × 4 m^2, slope: 7%); (1) unfertilized control (UC), (2) synthetic N fertilizer (conventional treatment, NPK), (3) pig manure (at N rates equivalent to the NPK treatment, OM), (4) synthetic N fertilizer (60% of applied N) plus pig manure (40% of applied N) (OM-NPK), (5) crop residue (equivalent to 40% of applied N by synthetic fertilizer, RSD), and (6) synthetic N fertilizer (60% of applied N) plus crop residue (40% of applied N) (RSD-NPK). All fertilizer treatments except for the RSD used in this study received equivalent amounts of N (280 kg N ha^{-1} y^{-1}), split into 130 kg N ha^{-1} in the wheat season and 150 kg N ha^{-1} in the maize growing season. The synthetic N fertilizer applied was ammonium bicarbonate, while all the treatments received calcium superphosphate (90 kg P_2O_5 ha^{-1} equivalent) and potassium chloride (36 kg K_2O ha^{-1} equivalent) as basal fertilization for both wheat and maize seasons. Pig manure applied to the wheat and maize was collected from the same pig farm, and had an average C:N ratio of 15:1. Mixed wheat and maize straw, with an average C:N ratio of about 61:1, was chopped into small pieces (~5 cm in length) and incorporated into the RSD and RSD-NPK treatment plots prior to planting maize (wheat). Pig manure, wheat straw, and maize straw N content were 0.4, 0.3, and 0.5%, respectively. All fertilizers were homogeneously applied by hand as basal fertilization on the same day when crops were planted. The soil thickness in the experimental site is about 60 cm. Each experimental plot was isolated by concrete dividing walls to a depth of at least 60 cm to avoid lateral movement, allowing simultaneous measurement of both surface runoff and interflow (Zhu et al., 2009).

2.2. Field experiment

Soil N_2O flux was measured from May 2013 to April 2014 using the static chamber-gas chromatography technique (Wang and Wang, 2003; Zheng et al., 2008). A stainless steel base collar (0.5 m × 0.5 m × 0.5 m) was inserted into the soil to a depth of approximately 0.1 m before measurements commenced, and it was kept in place over the entire measurement period. N_2O fluxes were measured at daily intervals beginning the first two weeks after