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Rapid recovery of nitrogen retention capacity in a subtropical acidic soil following afforestation

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ABSTRACT

Understanding soil nitrogen (N) dynamic and availability during afforestation (the conversion of cropland to forest plantations) is critical to maintain forest growth and long-term productivity, especially in rainfall-rich, subtropical region. However, only few studies have investigated the inherent N transformation processes involved in N availability in subtropical acidic soils. In a ^{15}N tracing study, nine soils from croplands, 10-y and 50-y afforested woodlands were sampled to investigate the changes in soil gross N transformation rates in humid subtropical China. Gross N transformation rates were not significantly different in soils under 10- and 50-y after afforestation. Compared to cropland, however, afforestation stimulated the rates of mineralization, microbial NH_4^+ immobilization and adsorption of NH_4^+, leading to a faster turnover of NH_4^+ pool in afforested soils. Moreover, afforestation inhibited autotrophic nitrification and resulted in NO_3^- production dominated by heterotrophic nitrification. Furthermore, afforestation significantly enhanced NO_3^- consumption mainly through the increase in microbial NO_3^- immobilization rather than dissimilatory NO_3^- reduction to NH_4^+ in soil. These differences in gross N transformation rates resulted in low net NO_3^- production and strong NO_3^- retention capacity in afforested soils, similar to that found in undisturbed natural forest. Our results suggest a rapid recovery (several years) of soil N retention following afforestation. Soil NO_3^- retention capacity was correlated positively with TOC, TN, WHC, CEC, Al, free Al oxide and exchangeable Al^{3+}, but negatively with pH, Ca and exchangeable Ca^{2+}, indicating that the absence of agricultural management (e.g., N fertilizer and liming) and alteration in soil environment by tree establishment are responsible for the recovery of N retention capacity in subtropical acidic soils during afforestation.

1. Introduction

Excessive logging and forest clearing in particular on steep slopes for agricultural cultivation are associated with environmental and ecological problems, e.g., soil erosion, biodiversity loss, desertification and climate change (Xu et al., 2006; Chakravarty et al., 2012; Gutiérrez Rodríguez et al., 2016). Such negative effects are much more pronounced in mountainous regions such as found in southwest China (Jiang et al., 2014). In the wake of severe drought in the Yellow River basin and massive flood in Yangtze River basin in 1997 and 1998, respectively, the Conversion of Cropland to Forest Program (CCFP) was initiated by the Chinese government in 1999 to increase the vegetation cover on steep slopes and to protect environmentally fragile areas (Xu et al., 2004). From 2000 to 2010, an area of approximately 4.9×10^6 ha was afforested/reforested globally, with more than 60% of the new forest being established in China (FAO, 2010). Factors that

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could limit the CCFP's positive effects were survival, low growth rate and poor health during forest establishment (McVicar et al., 2010; Zhang et al., 2016). Besides hydrological and landscape factors (Cao et al., 2011; Zhang et al., 2016), in particular nitrogen (N) limitation to tree growth, were considered to be the main factors affecting the success in afforestation (Mudge et al., 2014; Wen et al., 2016). Soil N accounts for approximately 88% of the global plant N demand (Schlesinger, 1997), and any change in soil N availability can greatly affect plant growth and productivity (Vitousek and Howarth, 1991). Therefore, it makes sense to investigate the effect of CCFP on soil N dynamic, availability and other related factors. In previous studies, the most widely used method to estimate soil N availability during afforestation was the net changes of different soil N pools (Mendham et al., 2004; Deng et al., 2014; Li et al., 2014; Dou et al., 2016). However, this does not differentiate the mechanisms underlying the change in soil N dynamic and availability (Hart et al., 1994; Zhu et al., 2014). Therefore, determining simultaneously occurring gross N rates, e.g., mineralization, nitrification or microbial ammonium (NH_4^+) and nitrate (NO_3^-) immobilization, can provide a more detailed and mechanistic understanding of the individual soil N cycling processes (Davidson et al., 1990; Müller et al., 2004; Zhang et al., 2013a; Hamilton et al., 2016), thereby elucidating the availability and retention mechanism of inorganic N during afforestation.

Soil NH_4^+, NO_3^- and dissolved organic N (monomers) are considered to be the main bioavailable N forms for microbial and plant uptake (Schimel and Bennett, 2004). In comparison to NO_3^-, NH_4^+ is less susceptible to ecosystem N loss through leaching, runoff or gaseous N production (Huygens et al., 2008). Thus, maintaining inorganic N being dominated by NH_4^+ rather than NO_3^- is an effective strategy to conserve N in soil in rainy subtropical and tropical region. It has been widely accepted that subtropical or tropical forests growing on highly weathered soils exhibit high N turnover rates (i.e., high inorganic N production and consumption) but low net NO_3^- production (Davidson et al., 2007; Zhang et al., 2013a) effectively reducing the availability of free reactive N. However, this N retention capacity can easily be affected by forest conversion to cropland, mainly attributing to changes in agricultural management strategy (e.g., tillage, the application of N fertilizer and liming) (Zhang et al., 2013b; Zhu et al., 2013a; Zhu et al., 2014). A common observations is that agricultural management significantly increases the activity and abundance of nitrifying microorganisms, e.g., ammonia-oxidizing bacteria (AOB), and therefore enhances NO_3^- production via autotrophic nitrification (i.e., oxidation of NH_4^+ to NO_3^-) (Chu et al., 2008; Zhang et al., 2013b; Zhu et al., 2013a). In comparison to the undisturbed natural forest, tillage increases the soil porosity, especially large pores, and allows greater movement of soil gases through the soil (Reicosky, 2002), which is also beneficial to the occurrence of autotrophic nitrification in soil under aerobic condition (Khalil et al., 2004). In addition, the removal of the litter layer during agricultural cultivation can increase soil temperature, thus may directly stimulate the rate of N mineralization and oxidation of NH_4^+ (Sharrow and Wright, 1977; Avrahami et al., 2003). Collectively, the conversion of forest to cropland can strongly increase NO_3^- production potential, and thereby may enhance NO_3^- loss in rainy subtropical and tropical region.

On the other side, the establishment of tree plantations during afforestation, absence of agricultural management (e.g., tillage, N fertilizer and liming) and alteration in soil properties, should potentially reduce N losses related to NO_3^- production via an effect on the interplay of the individual N transformations rates. Soil acidification may increase during afforestation (Berthrong et al., 2009; Fu et al., 2015), which is accompanied by increases in the concentrations of iron (Fe)-aluminum (Al) oxide (Harter, 2007) and in turn has an effect on soil N cycling, e.g., organic matter decomposition (Hall and Silver, 2013), oxidation of NH_4^+ to NO_3^- (Dollhopf et al., 2005; Jiang et al., 2014) and conversion of NO_3^- into organic N (Huang et al., 2016). Moreover, afforestation can improve soil quality via increasing soil organic C (SOC) and total N (TN) concentrations, ameliorating soil texture and water retention ability, and enhancing microbial activity (Yannikos et al., 2014; Gunina et al., 2017). Thus, microbial utilization of NO_3^- and subsequent turnover in soils are potentially enhanced. This has been confirmed by increased mineralization of organic N during forest establishment (Zhang et al., 2013b; Zhu et al., 2013a), by a relatively higher NH_4^+ production. Thus we hypothesized that during afforestation, an increased mineralization and microbial NO_3^- immobilization, and a decreased oxidation of NH_4^+ to NO_3^- would occur, lowering the NO_3^- concentration and increasing NH_4^+ concentration, recuperating a N-cycling capacity that is similar to native forests (Davidson et al., 2007; Zhang et al., 2011a, 2013a). Noticeably, this recuperation effect may depend on the duration of afforestation. Because the stimulatory effect of agricultural cultivation on NO_3^- production may be still persist in the early afforestation stage (it is expected to last around 10 years), soil N retention capacity could not be recovered. As forest age increases, soil environment becomes more and more steady, leading to a stabilization of soil C and N stocks and microbial community structures that are more typical of native forests (approximately 30–50 years) (Buckley and Schmidt, 2003; van der Wal et al., 2006; Fu et al., 2015; Gunina et al., 2017), and thereby recuperates soil N retention capacity.

To verify our hypothesis, soil samples were collected from six woodlands in subtropical southwest China, three at the early tree development stage (10 years after afforestation) and other three at the long-term tree development stage (50 years after afforestation); three adjacent croplands were chosen as control in this study. Soil gross N transformation rates were determined using ^{15}N tracing techniques combined with a ^{15}N tracing model (Müller et al., 2007). The characteristic of N transformation in studied soils were compared with those in adjacent natural forest soils, in which the relevant data were collected from previous literature. In addition, indicators related to agricultural management (e.g., pH, Ca) and soil quality improvement (e.g., TOC, TN, CEC) during afforestation were determined to analyze interactions of gross N transformation rate and N retention capacity with the prevailing factors.

2. Material and methods

2.1. Site description and sample collection

Sampled sites were located in Maocun karst experimental site (25°10′11″–25°12′30″ N and 110°30′00″–110°33′45″E), 30 km to the southeast of Guilin City, Guangxi Province, China, which is characterized by a subtropical monsoon climate with an average annual temperature of 18.6 °C and annual precipitation of 1980 mm (Huang et al., 2015). The rainy season mainly occurs from March to August. The entire region is characterized by a similar mean altitude (approximately 160 m) and steep slopes (approximately 20°) as well as a geological background on Tertiary red sandstone. Soil at the sites was Haplic Ferralsol (IUSS Working Group WRB, 2014), with a typical soil depth of 60 cm. In this region, forest logging to agricultural cultivation on steep slopes began in 1930s and lasted until 1998. Forest clearing and cropland cultivation caused great losses of nutrients in deforested soil. After soil fertility decreased to a low level and could not effectively maintain crop productivity, the cleared land had been afforested by local farmers, which started in 1940s. Since 1999, Conversion of Cropland to Forest Program (CCFP) has been initiated by the government, and a large cropland area was converted to woodland plantation of broadleaf trees. *Castanopsis fargesii* was the dominant tree species used for afforestation.

In May 2015, soil samples were collected from *Castanopsis fargesii* plantation at the early (10 years) (A10) and long-term (50 years) (A50) development stage of afforestation. The adjacent cropland (A0) was also collected as a control. The cropland for last 26 years was cropped with corn and soybeans fertilized with approximately 180, 45, 120 and