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Dynamics of soil nitrogen availability during post-agricultural succession in a karst region, southwest China

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ABSTRACT

Soil nitrogen (N) availability is crucial in governing the dynamics of ecosystem structure and function. However, the variation pattern of soil N availability during post-agricultural succession has been poorly understood for karst regions. Here, soil N availability variables, including concentrations of soil total N (TN), dissolved inorganic N (DIN = ammonium (NH_4^+) + nitrate (NO_3^-)), dissolved organic N (DON), rates of net N mineralization and nitrification at different successional stages, i.e. cropland, grassland, shrubland and secondary forest were investigated at a regional scale, in order to get a general pattern of soil N availability dynamics following agricultural abandonment in the karst region of southwest China. Concentrations of soil TN, soil NO_3^-, DIN, net N mineralization and nitrification rates increased from grassland to forest. Soil NO_3^- concentration in secondary forest (37.71 ± 5.01 mg N kg^{-1}) reached the level in cropland (31.01 ± 2.93 mg N kg^{-1}). Soil NO_3^-:NH_4^+ ratio in grassland was not significantly different from 1, but increased directly and reached 13.02 ± 1.16 in secondary forest, equivalent to the level in cropland (15.15 ± 1.98). The dynamics of soil DIN:DON ratio followed the same pattern as soil NO_3^-:NH_4^+ ratio. Our study suggests that soil N availability increases and soil N cycling becomes progressively open following agricultural abandonment in the karst region, southwest China.

1. Introduction

Nitrogen (N) is an essential macronutrient for plant growth and is often the primary limiting resource for productivity of many terrestrial ecosystems (LeBauer and Treseder, 2008). Since most N in the terrestrial biosphere is stored in the soil (Wang et al., 2010), the transformations of soil N, including mineralization of organic-N to ammonium (NH_4^+) and nitrification of NH_4^+ to nitrate (NO_3^-), largely control N availability to plants (Schimel and Bennett, 2004). Soil N availability is tightly linked with ecosystem productivity and carbon (C) storage, as well as NO_3^- leaching and nitrous oxide emission (Wolf et al., 2011). Furthermore, soil N availability has been shown to primarily control the process of plant community redevelopment after a disturbance (i.e. secondary succession) (Mclendon and Redente, 1992; Paschke et al., 2000). In the case of insufficient supply of soil N, spontaneous succession on abandoned cropland may slow down or even be trapped in grass-dominated vegetation. Therefore, understanding of soil N availability and transformations following agricultural abandonment is undoubtedly necessary to predict the secondary succession rate and/or ecosystem C sequestration capacity (Wen et al., 2016).

As microbial-mediated processes, soil N transformations (i.e., mineralization and nitrification) are influenced by a suite of factors including soil physiochemical properties, substrate quantity and quality, microbial community composition and activity, and temperature and moisture. All these factors are likely to change with the evolution of vegetation mainly due to variations in the quantity and quality of organic inputs to the soil from litters and roots (Perez-Bejarano et al., 2010; Zhang et al., 2013), which in turn affects the pattern of soil N availability and transformations through vegetation succession (Chapman et al., 2006; Chu and Grogan, 2010).

Considerable attention has been given in recent decades to changes of soil N availability and transformations in relation to vegetation succession (Paschke et al., 2000; Pérez et al., 2004; Yan et al., 2009; Nave et al., 2014; Mylliemngap et al., 2016; Wang et al., 2016). However, results of these studies diverge greatly. For example, net N mineralization rate has been found to increase (Kristensen and

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Henriksen, 1998; Pérez et al., 2004), decrease (Merilä et al., 2002), or follow a ‘U-shaped’ temporal trend through succession, i.e., highest in early and late stages and lowest in an intermediate stage, e.g. in the subtropical forests of eastern China (Yan et al., 2009) and in Michigan jack pine forests, USA (LeDuc and Rothstein, 2010). This discrepancy is probably due to the wide differences in land-use history, species composition, and soil properties across studies. For example, vegetation succession after fire often involves a pulse of inorganic N availability early due to accelerated soil N mineralization but then declines at later stages, while vegetation succession on abandoned agricultural field generally starts with low N availability and recovers over time with succession (Vitousek et al., 1989; Davidson et al., 2007).

Karst terrain, which is typically developed on carbonate rocks (e.g. limestone and/or dolomite), is a major component of the earth's surface system, accounting for 15–20% of the Earth's ice-free land surface (Engel, 2011), and about 36% of the national land in China (Jiang et al., 2014). There is about 51 million ha of contiguous exposed/outcropped carbonate rock area (or karst area), accounting for 5.8% of the national land, in the southwest China (Jiang et al., 2014). During the period from 1949 to the end of the 1970s, massive deforestation and agricultural expansion led to widespread degradation in the karst areas of southwest China (Wang et al., 2004). Since the 1970s, however, the Chinese government has implemented several nationwide ecological projects with the goal of increasing forest cover, including the slope land conversion program (SLCP, also called Grain-for-Green). As a consequence, a large proportion of slope and barren lands has been reverted to forests or grasslands through plantation or natural regeneration, particularly in hilly and mountainous areas (Liu and Diamond, 2005).

Agricultural abandonment and subsequent spontaneous vegetation succession play an important role in ecosystem restoration (Prach et al., 2001). It has been shown that vegetation recovery in degraded karst areas could substantially improve soil physicochemical and biological properties (Zhu et al., 2012), reduce soil erosion, and increase soil organic C (SOC) storage (Liu et al., 2013). However, little is known about soil N dynamics during post-agricultural succession in the karst region of southwest China (Zhang et al., 2015; Wen et al., 2016). This in turn limits our ability to predict the functioning and resilience of these ecosystems, and to devise sustainable restoration strategies for the fragile karst areas.

In a previous study, we investigated soil N dynamics along a post-agricultural succession sequence in a karst area, southwest China (Wen et al., 2016). We found that N recovered rapidly follow agricultural abandonment, suggesting N would not be the limiting nutrient for secondary succession and ecological restoration in the karst region of southwest China. However, due to only one succession sequence was included in that study, it is not clear whether the observed patterns of N dynamics following agricultural abandonment are also applicable at a regional scale. In the present study, soil N availability variables, including concentrations of NH_4^+, NO_3^-, dissolved organic N (DON), rates of net N mineralization and nitrification were investigated in cropland, grassland, shrubland and secondary forest over a region scale in order to get the general patterns of soil N availability dynamics following agricultural abandonment in the karst region of southwest China.

2. Materials and methods

2.1. Study region

The study region (23°40′ N–25°25′ N, 107°35′ E–108°30′ E) is located in the northwest of Guangxi Zhuang Autonomous Region of southwest China. Mean annual air temperature (MAT) is 17.8–21.1 °C, and mean annual precipitation (MAP) varies from 1346 to 1640 mm with the period from April to September being wet season and that from October to March being dry season (Li et al., 2017). The region is characterized by a typical karst landscape with gentle valleys surrounded by steep hills. The lithology in the karst areas is limestone, dolomite and their mixtures. The soil is calcareous lithosols (limestone soil) over both limestone and dolomite according to the FAO/UNESCO classification system (Anon, 1974).

2.2. Field sampling

A space-for-time substitution approach was used in the current study. Grassland, shrubland and secondary forest, which naturally regenerated from maize-soybean fields, were selected to represent three post-agricultural successional stages with cropland as reference. The croplands were corn-soybean rotation systems with fertilization rates of about 150, 60 and 120 $kg\ ha^{-1}\ yr^{-1}$, respectively, for N, P and K. Fertilization stopped after cropland abandonment. The land use history for grassland, shrubland and secondary forest was obtained by inquiring native residents. The duration of agricultural abandonment varied from 5 to 10 years, 10 to 20 years and 30 to 50 years for grassland, shrubland, and secondary forest, respectively.

Field sampling was carried out from the mid of May to early June 2015. The number of sampling sites for grassland, shrubland and secondary forest was 18 each. However, only 12 sites were selected for the maize-soybean fields, since most maize-soybean fields were converted to orchard, plantation forest or subject to post-agricultural succession after abandonment. In total, 66 sites were selected. At each sampling site, an area of 20 m × 20 m was selected. The distance for the adjacent sampling sites ranged from about 50 m to 10 km across the karst areas of Huanjiang County, since the studied region was interwoven with non-karst areas. Given that obvious organic layer was absent for most sites, only mineral soils to a depth of 0–15 cm were collected. 10 to 15 soil cores were collected at each site and mixed thoroughly to form a composite sample. Additional soil cores were collected to determine bulk density (BD). Fresh soil samples were immediately sieved (< 2 mm) on site with roots and stone removed, and stored in a cool box until transported to the laboratory.

2.3. Chemical analysis

A subsample of each fresh soil sample was extracted with 0.5 M K_2SO_4 (1:5 soil to solution ratio) and then filtered through a plastic syringe fitted with a 0.45-μm filter. NH_4^+ and NO_3^- concentrations were determined colorimetrically on a flow injection analyzer (FIAstar 5000, FOSS, Sweden). Total dissolved N (TDN) was analyzed after persulfate oxidation, through which NH_4^+ and dissolved organic N (DON) in the extracts were completely converted to NO_3^-, and then measured as NO_3^- (Hood-nowotny et al., 2010). DON concentration was calculated as the difference between TDN and dissolved inorganic N (DIN = $NH_4^+ + NO_3^-$) concentrations. Final values of N pools were presented as $mg\ N\ kg^{-1}$ dry soil, where dry soil refers to constant weight after drying a subsample at 105 °C. Net rates of N mineralization and nitrification were determined by a 10-day aerobic incubation in the dark at 20 °C. NH_4^+ and NO_3^- concentrations before and after incubation were analyzed as described above. Net N mineralization rates were determined from the difference between DIN pools at the start and end of the incubation, and the results were presented on a basis of mean daily inorganic N production. Net nitrification rates were determined from the difference between NO_3^- at the start and end of the incubation, and the results were presented on a basis of mean daily NO_3^--N production. SOC was measured by wet oxidation with $KCr_2O_7 + H_2SO_4$ and titrate with $FeSO_4$. Total N (TN) was analyzed with an elemental analyzer (EA 3000, EuroVector, Italy). Soil pH (1:2.5 soil to water ratio) was measured using a pH meter (FE20K, Mettler-Toledo, Switzerland). Soil particle size distribution was determined with a laser diffraction particle size analyzer (Mastersizer, 2000, Malvern, UK). Exchangeable calcium (Ca) and magnesium (Mg) were extracted with 1 $mol\ L^{-1}$ ammonium acetate buffered at pH 7.0, and determined using ICP-OES