Patterns and regulating mechanisms of soil nitrogen mineralization and temperature sensitivity in Chinese terrestrial ecosystems

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ABSTRACT

The mineralization (or decomposition) processes of soil organic matter (SOM), from organic to inorganic, play important roles in supplying most of nutrient for plant growth. Thus, understanding the spatial pattern and regulating mechanisms of soil nitrogen mineralization rate (N_{min}) and its temperature sensitivity (Q_{10}) is of great significance for evaluating ecosystem productivity and the supply of soil available nitrogen (N). Here, data derived from 212 published papers in Chinese terrestrial ecosystems were used to explore the spatial pattern and regulating mechanisms of N_{min} and Q_{10}. The results showed that the average N_{min} was $2.78 \pm 0.18\,\mathrm{mg\,N\,kg^{-1}\,d^{-1}}$ at an incubation conditions of 25 °C across Chinese terrestrial ecosystems, and it decreased gradually with increasing latitude ($P < 0.01$). The N_{min} values were the highest in farmlands ($3.08 \pm 0.20\,\mathrm{mg\,N\,kg^{-1}\,d^{-1}}$), followed by forests ($2.35 \pm 0.42\,\mathrm{mg\,N\,kg^{-1}\,d^{-1}}$) and grasslands ($0.57 \pm 0.13\,\mathrm{mg\,N\,kg^{-1}\,d^{-1}}$). The Q_{10} values differed significantly among different ecosystems ($P < 0.01$), with an average of 1.58. The Q_{10} values increased significantly with increasing latitude, supporting the hypothesis that the Q_{10} values are higher in colder regions. Path analysis showed that N_{min} is mainly affected by mean annual temperature and SOM content, whereas Q_{10} is primarily affected by soil total nitrogen. The activation energy (E_a) of N_{min} and substrate quality index (A) was strongly negatively correlated, indicating that the carbon-quality temperature hypothesis is applicable to N_{min} at a large spatial scale. These findings provide new evidence that soil N availability in colder regions is likely to increase due to higher Q_{10} under global warming scenarios, which may promote ecosystem productivity at higher latitudes.

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1. Introduction

The capacity of soil nitrogen (N) supply is a key element influencing plant growth (Näsholm et al., 1998) and limiting primary productivity in most natural ecosystems (Vitousek and Howarth, 1991; Elser et al., 2007). A requirement for N fertilizer is therefore pervasive in intensive agricultural ecosystems. Soil N availability is determined to a large extent by the processes of soil N mineralization (N_{min}), which converts soil organic N into inorganic N from soil organic matter (SOM) with the help of soil animals and microorganisms (Chapin III et al., 2011). Some studies have demonstrated that the rates of N_{min} are mainly influenced by temperature and tend to increase gradually with increasing temperature in a given temperature range (Sierra, 1997; Guntinas et al., 2012). Under the context of global warming, even a slight change of N_{min} in response to temperature shift would affect soil N availability and thus influence primary productivity to some extent (Stocker et al., 2013). However, since these previous researches were mainly conducted at several sites or within a small region, it remains unclear whether the phenomena or the underlying mechanisms observed at several smaller sites are applicable at the large scale.

Temperature affects the processes of N_{min} through altering the community composition and quantity of soil microorganisms (Guntinas et al., 2012). The temperature sensitivity of N_{min} (Q_{10}) has been widely used as an important ecological parameter in models of carbon (C) and N cycles to depict the responses of N_{min} with an increase in temperature of 10 °C (Reichstein et al., 2005). In earlier models, the Q_{10} values were commonly considered to be constant, with an average of 2. However, some experiments demonstrated that the Q_{10} values vary spatially among different ecosystems (Lenton and Huntingford, 2003), depending on the

conditions of soil temperature, soil water content, and SOM quality as well as different vegetation types (Wetterstedt et al., 2010; Craine and Gelderman., 2011; Weedon et al., 2013). Given that these factors are spatially heterogeneous, the Q_{10} values may also vary among different geographic locations. It is expected that even a small deviation of Q_{10} values may result in apparent biases in the estimation of N_{min} at a large scale in models. Therefore, understanding the spatial pattern and regulating mechanisms of N_{min} and Q_{10} is of great significance in order to precisely evaluate the supply of soil available N and for the sustainable management of anthropogenic ecosystems.

Few studies have investigated changes in the Q_{10} values of N_{min} with respect to large-scale environmental variations, although several investigations have been conducted with regards to the spatial patterns of Q_{10} for soil C mineralization or respiration (Davidson and Janssens, 2006; Peng et al., 2009; Song et al., 2014). Furthermore, the carbon-quality temperature hypothesis (CQT) was proposed to explain the underlying mechanisms of SOM decomposition on the basis of enzyme kinetics principles; that is, with more biochemical recalcitrant SOM, the Q_{10} for soil microbial respiration is greater (Bosatta and Agren, 1999). This hypothesis has been verified both directly and indirectly with respect to soil C mineralization or soil respiration (Fierer et al., 2005; Conant et al., 2008; Craine et al., 2010; Wang et al., 2014). Recent studies have demonstrated that soil C and N mineralization are closely coupled, irrespective of vegetation types (Quan et al., 2014; Gutiérrez-Girón et al., 2015). However, it remains unclear whether the CQT hypothesis is applicable to soil N mineralization, especially at a regional or global scale.

Here, we collected 212 published papers on soil N mineralization in Chinese terrestrial ecosystems, and categorized the data to explore the spatial patterns and regulating mechanisms of N_{min} and Q_{10}. The main objectives of this study were to: (1) investigate the spatial patterns and regulating factors of N_{min} and Q_{10}, (2) explore the underlying mechanism of N_{min} and Q_{10} at a regional scale, and (3) evaluate whether the CQT hypothesis is applicable to soil N mineralization at a regional scale.

2. Methods

2.1. Data collection

We compiled the available data of soil N mineralization rates in Chinese terrestrial ecosystems from papers published from 1990 to 2014, which were downloaded from the Web of Science (www.webofknowledge.com) and China National Knowledge Infrastructure (http://epub.cnki.net) databases. Only published data from laboratory experiments were extracted for the analysis of potential N_{min} at 25 °C incubation. Furthermore, data from experiments using different incubation temperatures were collected to calculate the Q_{10} values of N_{min}. In total, data from 167 published papers were used to investigate N_{min} at 25 °C (Fig. 1A and Table S1), and data from 60 published papers were used to calculate the Q_{10} values among Chinese terrestrial ecosystems (Fig. 1B and Table S2).

The original data were first extracted from tables or graphs using the GetData Graph Digitizer software (version 2.24, Russian Federation). Furthermore, auxiliary information was collected, such as longitude, latitude, altitude, mean annual temperature (MAT), mean annual precipitation (MAP), ecosystem type, pH, SOM content, and soil total nitrogen (TN). The forest data were divided into the following four types according to their morphological features in order to explore the influence of forest types on N_{min} and Q_{10}: deciduous coniferous forest (DCF), evergreen coniferous forest (ECF), deciduous broadleaved forest (DBF), and evergreen broadleaved forest (EBF).

2.2. Data calculations

The potential rates of soil N_{min} under 25 °C incubation were selected to depict the spatial patterns of soil N mineralization, because 25 °C is considered as the optimal incubation temperature for microbe growth and activity (Wang et al., 2006). The average N_{min} for a specific site was used when soils were incubated at different soil water content.

The Q_{10} values were calculated according to Eq. (1) (Janssens and Pilegaard, 2003):

$$Q_{10} = \left(\frac{RN_2}{RN_1}\right)^{[10/(T_2-T_1)]} \tag{1}$$

where RN_1 and RN_2 are the soil net N mineralization rates (mg N kg^{-1} d^{-1}) at incubation temperatures T_1 and T_2, respectively.

The apparent activation energy (E_a, kJ mol^{-1}) of soil N_{min} rate, as an enzyme kinetic parameter representing the difficulty of a reaction, was calculated using the Arrhenius equation as shown in Eq. (2) (Hamdi et al., 2013):

$$RN = A \times e^{-E_a/RT} \tag{2}$$

where RN represents the soil net N mineralization rate (mg N kg^{-1} d^{-1}), A is a pre-exponential factor known as the substrate
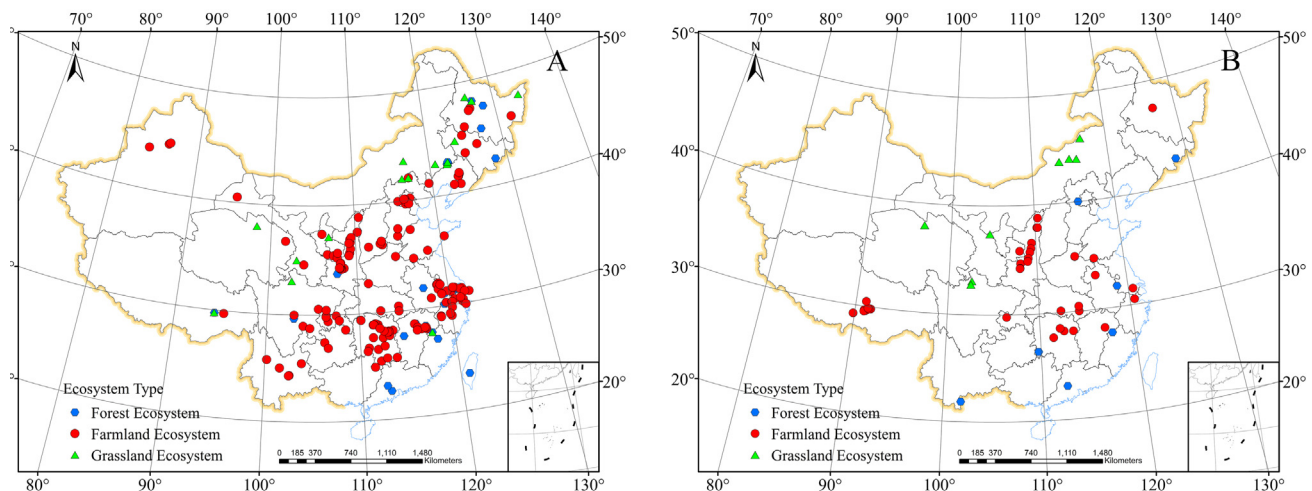

Fig. 1. Spatial distribution of sampling sites from published articles focusing on soil net nitrogen mineralization rates (A) and temperature sensitivity (B).