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Factors contributing to soil nitrogen mineralization and nitrification rates of forest soils in the Japanese archipelago

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ABSTRACT

Nitrogen (N) is the primary limiting nutrient for forest production. Therefore, understanding how environmental factors affect N transformation rates is essential for the provision of sustainable ecosystem services. Because these factors are interlinked, it is important to consider direct and indirect structural relationships to better understand the factors contributing to N transformations. In this study, we analyzed the structural cause–effect relationships surrounding N transformations by structural equation modeling using a database containing net and gross N transformation rates and related soil chemical properties from 38 sites across the Japanese archipelago. The average net N mineralization and nitrification rates in the Japanese forest soils were 0.62 ± 0.68 and 0.59 ± 0.65 mg N kg^{-1} d^{-1}, respectively, and gross N mineralization and nitrification rates were 4.22 ± 3.59 and 0.98 ± 0.68 mg N kg^{-1} d^{-1}, respectively. Compared with previous large scale studies, net and gross N transformation rates in Japanese forest soils were considerably diverse despite their relatively small land area and were representative of temperate forest ecosystems. Structural equation modeling analysis showed that net N transformations were directly affected by gross N transformations, which in turn were significantly and directly affected by soil organic matter contents. Soil organic matter was significantly affected by organic layer amount, tree species and soil group. The effect of soil group was the greatest among these factors, suggesting that soil organic matter contents in Japanese forest soils were mainly influenced by soil parent materials. This was especially evident for Andosols, which are derived from volcanic sediments and contain large amounts of soil organic matter leading to high N transformation rates in the Japanese forest soils. Among the factors related to organic layers and mineral soil layers, soil organic matter content and organic layer amount, which represent substrate availability, had significant effects on gross and net N transformation rates. However, by refining the scale of the dataset using soil groups/soil parent materials, the influence of substrate quality and soil chemical properties on N transformations was suggested. From the current dataset, it was indicated that soil parent materials were the most important factor controlling

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the pattern of N transformations in the soil of Japanese forest ecosystems. This conclusion should be repeatedly refined considering the spatial distribution of factors such as climatic conditions and forest types with additional site datasets obtained from future surveys.

1. Introduction

Soil nitrogen (N) transformations (i.e., N mineralization and nitrification) are key processes regulating ecosystem services such as forest productivity, soil fertility and streamwater quality, because N is a limiting nutrient in forest ecosystems (Vitousek and Howarth, 1991; Mitchell, 2011). Understanding how environmental factors influence N transformations is essential for the provision of sustainable ecosystem services, especially in a forest ecosystem.

Although there are a number of studies that considered the effects of various environmental factors on N transformations, the major controlling factors changed among studies according to the scale and spatial range of the study sites (Aerts, 1997). For example, at larger spatial scales up to the global scale, climatic conditions and substrate amounts were significant controlling factors (Booth et al., 2005; Colman and Schimel, 2013). At smaller scales, site characteristics such as vegetation type (Hobbie, 1992, 1996, 2015), soil acidity (Cookson et al., 2007; Tian et al., 2012), salinity (McClung and Frankenberger, 1985; Noe et al., 2013) and soil water content (Gutiérrez-Girón et al., 2014) become more important. Some of these factors are interlinked, such that some factors directly control N transformations, while others mediate them by affecting the direct factors (Binkley and Giardina, 1998). For example, soil organic matter content, which directly affects N transformation rates (Booth et al., 2005; Cookson et al., 2007), is affected by organic matter decomposition in the litter layer (e.g. Berg and McClaugherty, 2008). Decomposition of the litter layer is influenced by the quantity and quality of the litter layer (Coûteaux et al., 1995; Fierer et al., 2005), and litter layer characteristics are constrained by vegetation type (Hobbie, 1992, 1996; Ono et al., 2013) and climatic conditions (Coûteaux et al., 1995; Aerts, 1997; Inagaki et al., 2010). Therefore, it is important to consider both direct and indirect cause–effect structural relationships to better understand the factors contributing to N transformations. For this analysis, a wide ranging dataset containing geographical locations, N transformation rates and comprehensive environmental and soil characteristics is absolutely necessary. However, there are few published large scale studies based on exhaustive surveys (Colman and Schimel, 2013) or literature surveys (Booth et al., 2005) dealing with N transformation rates and related environmental and soil characteristics. Previous studies conducted regression analysis (Booth et al., 2005) and structural equation modeling (SEM; Colman and Schimel, 2013) to clarify the effects of environmental factors on N transformation rates. To conduct structural analysis of cause–effect relationships surrounding N transformations, a database containing a wide range of items obtained with unified protocols through many survey points is essential. To our knowledge, in East Asia, and in Japan particularly, there is no suitable information source or database available for such intensive statistical analysis. Although there have been two previous large-scale ecosystem surveys in Japan [Forest Soil Survey (Editorial committee of "Forest soils in Japan", 1983) and Japan-International Biological Program (Kira et al., 1978)], these surveys did not consider the possible secondary uses of the datasets; they contain limited information on nutrient cycling in Japanese forest ecosystems.

The Japanese archipelago ranges approximately 3000 km from north to south, and the climatic zones ranges from cool temperate to subtropical. The biodiversity of forest ecosystems of Japan is considerably high because of the wide range of its geographical and climatic distribution and the diverse use-history of the forest (Ministry of the Environment, 2010). Thus, soil N transformations in Japanese forest ecosystems are likely to be influenced by these conditions.

Andosols/Andisols (IUSS Working Group WRB, 2014; Soil Survey Staff, 2014), which are generated from volcanic sediments, are broadly distributed throughout forest soils in Japan (Nanko et al., 2014). Andosols/Andisols are very specific soil type characterized by a high organic matter content (Batjes, 1996; Imaya et al., 2010), low bulk density (Nanko et al., 2014), and high activated aluminum (Al) content (Wada, 1986). It has been suggested that soil group/soil parent material significantly affects N dynamics in forest ecosystems (Reich et al., 1997). Therefore, soil N transformations in Japanese forest ecosystems might be influenced by soil parent materials, as identified by soil groups, and the factors affecting N transformations might be different among soil groups.

Recently in Japan, there has been increasing concern about the effects of climate change (IPCC, 2007) and the increase in cross-border air pollutants from the continent (Ministry of the Environment, 2014) on nutrient cycling in forest ecosystems. Although applying ecosystem models is efficient to evaluate and predict these effects, large-scale ecosystem databases, which are crucial for validating these ecosystem models, are very limited. To solve this situation, a database was recently developed on the biogeochemical N properties of forest soils in the Japanese archipelago (Urakawa et al., 2015). This database contains environmental items such as mean annual temperature and precipitation, dominant tree species and physicochemical soil properties at approximately 40 sites across Japan. The database also contains both net and gross rates of N mineralization and nitrification, measured independently by laboratory incubation for 4 weeks at constant temperature for net rates and by the ^{15}N isotope dilution method for gross rates. Gross rates, which reflect microbial activities, are a more direct and precise index than net rates when discussing N transformations (Davidson et al., 1992; Schimel and Bennett, 2004). It is common to observe substantial rates of gross mineralization and nitrification while small net rates are observed, because net rates only account for the net differences in NH_4^+ and NO_3^- concentrations for a given time interval (Hart et al., 1994b). On the other hand, net N transformation rates still provide a useful index of plant N availability (Davidson et al., 1992; Schimel and Bennett, 2004), providing important information for evaluating soil fertility and ecosystem services. However, there are few studies in which both gross and N transformation measurements have been conducted independently (Booth et al., 2005). It is meaningful to compare N transformation rates, which are considered to be influenced by ecological and pedological characteristics of Japan, with those of other temperate forest ecosystems.

The objectives of this study were (i) to clarify the characteristics of net and gross rates of N transformation in forest soils in Japan; and (ii) to elucidate the structural cause–effect relationships of N transformation rates and associated environmental factors, especially considering the effect of soil parent materials, which are