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Evaluating the mechanisms of the impacts of key factors on soil soluble organic nitrogen concentrations in subtropical mountain ecosystems

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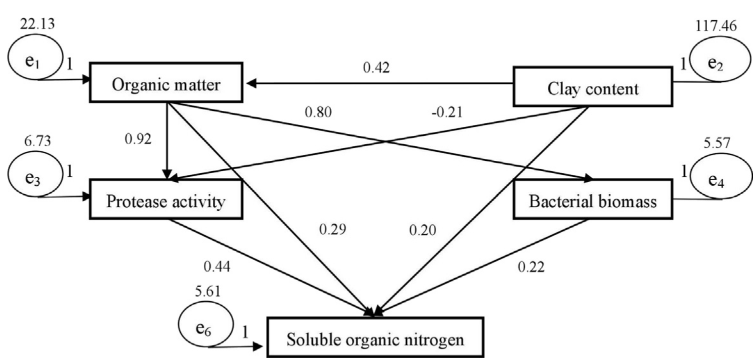
HIGHLIGHTS

- The mechanism of the impacts of key factors on SON was evaluated by SEM and GRA.
- Organic matter, clay content, protease activity and bacterial biomass are key factors.
- Organic matter, clay content and protease activity had the highest total impacts.
- Protease activity had the highest direct impact.
- Organic matter and clay content had the highest indirect impacts.

GRAPHICAL ABSTRACT



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ABSTRACT

Soil soluble organic nitrogen (SON) concentrations in terrestrial ecosystems were influenced differently and substantially by both biotic and abiotic factors. This study aimed to ascertain the mechanisms of the impact of the key factors on the SON concentrations of subtropical mountain ecosystems in southeastern China using an integrative approach, which combined a field plot survey, gray relational analysis and structure equation modeling. The results showed that the soil organic matter, clay content, protease activity and bacterial biomass were the key factors controlling the dynamics of the SON concentrations in subtropical mountain ecosystems. Protease activity, by catalyzing the degradation of complex organic nitrogen to SON, had the highest direct influence on the SON concentrations among all of the impact factors with direct impact effect of 0.44. Organic matter, which serves as a primary source of SON and can increase soil protease activity and bacterial biomass, contributed the most significantly to the SON concentrations in both direct and indirect pathways with total impact effects of 0.87. Clay, by adsorbing SON and affecting organic matter accumulation and protease activity, also had important direct or indirect influences on the SON concentrations with total impact effects of 0.48. The impact of the bacterial biomass on the SON concentrations was likely to be concealed by accompanying nitrogen-degrading enzyme activity with total impact effects of 0.22. Thus, the organic matter, clay content and protease activity exerted greater total impact effects on the SON concentrations compared with the bacterial biomass. Protease activity and organic matter had a greater positive direct impact on the SON concentrations compared with the bacterial biomass and clay content, while organic matter also had greater positive indirect impacts on the SON concentrations than

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did the clay content. This study's results could help to elucidate the differential mechanism of SON dynamics among various terrestrial ecosystems.

1. Introduction

A growing body of research has shown that plants can directly take up soluble organic nitrogen (N) (SON), such as amino acids from the soils in various terrestrial ecosystems (e.g. Näsholm and Persson, 2001; Näsholm et al., 2009; Finzi and Berthrong, 2005; Wang et al., 2012; Wei et al., 2013; Gao et al., 2014). However, the exact nutritional role of the direct uptake of SON by plants is still unclear. Alternatively, it has been suggested that the hydrolysis of soil organic N to produce SON is the rate limiting step for N mineralization and supply (Chen and Xu, 2008). Soil SON concentrations can be affected by both biotic and abiotic factors, such as the soil type, vegetation cover, management practices, and soil physical, chemical and biological properties (e.g., Willett et al., 2004; Yang et al., 2012; Chen and Xu, 2008; Xing et al., 2010, 2011; Zhou et al., 2012). Most of the current studies have focused on the impacts of the land use type, climate, vegetation cover and management practices, as well as soil chemical and biological properties, on the soil SON concentrations. The results reported by Willett et al. (2004), Burton et al. (2007), Chen et al. (2005b), Chen and Xu (2008), Zhou et al. (2012, 2016) or Huang et al. (2013) indicated that the soil SON concentrations were affected by the land use type, climate, vegetation cover and management practices because of the differences in plant growth characteristics, metabolism and productivity which contributed substantially to the differences in the quality and quantity of organic inputs (e.g., 1eaf litter, woody debris, roots, root exudates and fertilization) and the mineralization of organic matter in the soils. Pearson correlation analysis has been used in numerous studies (Xing et al., 2010, 2011; Yang et al., 2012; Huang et al., 2013, 2014; Zhou et al., 2015; Zhong et al., 2017) to identify the correlation between the SON concentrations and a single soil chemical or biological properties. The results showed that the SON concentrations were substantially related to the soil total C and N ($r = 0.764^{**} \sim 0.916^{**}$, $p < 0.01$), microbial biomass carbon and microbial biomass nitrogen ($r = 0.808^{**} \sim 0.859^{**}$, $p < 0.01$), the biomasses of microorganisms, bacteria and fungi ($r = 0.620^{**} \sim 0.934^{**}$, $p < 0.01$) or the activities of urease, protease and asparaginase ($r = 0.673^{**} \sim 0.924^{**}$, $p < 0.01$), which acted as the sources of the SON or affected the decomposition of complex organic N into SON. Obviously, almost all of the recent impact mechanistic studies on the soil SON concentrations used either the theoretical analysis of a single factor or a linear correlation analysis to describe the relationship between a single impact factor and the soil SON, which could only indicate the degree of correlation between the soil SON concentration and the single impact factor, which could not clearly illuminate the comprehensive impacts of multifactors on the soil SON concentrations. The mechanisms of the impact of diverse factors on the soil SON concentrations in terrestrial ecosystems, including the impact pathway and the difference of the impact effect, were still unclear.

The soil SON concentrations in terrestrial ecosystems were interactively affected by diverse impact factors. The relationships between the soil SON concentrations and impact factors were generally complicated. Some factors might have extensive or direct impacts on the SON concentrations as key factors, while others just had indirect or lower effects on the soil SON concentrations as secondary factors. It is necessary to recognize the differences in the impact mechanism of various factors on the SON concentrations to better understand the nature, characteristics and eco-functions of the SON in the ecosystems. Gray relational analysis (GRA) is a useful statistical method to quantitatively explain uncertain situations of multifactors in complex gray systems (Deng, 1989), which can clearly recognize close levels of correlation among diverse impact factors using the gray relational degree (Deng, 1996). Structural equation modeling (SEM) allows for both the direct and indirect theoretical causal relationships between intercorrelated variables to be tested, and for potential multivariate relationships to be identified (Grace, 2006) which can solve the limitation of the traditional univariate hypothesis on the study of correlations (Grace and Bollen, 2008). This method enables the examination of the direct and indirect effects of the observed multiple variables in a model in which the regressions of the relationships between the variables can be simultaneously evaluated (Malaeb et al., 2000; Arhonditsis et al., 2006). We hypothesized that the impact mechanisms of multiple factors on the soil SON concentrations in terrestrial ecosystems might be clearly recognized by the integrative method of GRA and SEM. Thus, in this study, the mechanisms of the impact of key biotic and abiotic factors on the soil SON dynamics in subtropical mountain ecosystems located in southeastern China, including forest, tea and fruit tree ecosystems, were discussed and illuminated by an integrative approach combining a field plot survey, GRA and SEM.

2. Materials and methods

2.1. Site description and soil sampling

Three different mountain ecosystems, i.e., forestry, tea and fruit tree ecosystems, located in Fujian Province, southeastern China, were selected as study objects. The ecosystem descriptions are shown in Table 1. The forestry ecosystem located in Nanping, Northern Fujian, includes three types of forest plantations planted in 1996, i.e., Chinese Fir (designated 'CF'), Mixed Forest Species (designated 'MFS') and Broadleaf Phoebe (designated 'BP'). One field site in each forest plantation was established. In total, three field sites were established in the forestry ecosystem used. The original stocking densities of 'CF', 'MFS' and 'BP' were 1800, 2400 (half for each mixed species) and 1260 strains per ha, respectively. These three types of forest plantations have never been thinned since their establishment. The combined fertilizers (N:P:K 15:15:15) were applied in these three forest sites at the same rates of 50 kg N ha^{-1}, 229 kg P_2O_5 ha^{-1} and 120 kg K_2O ha^{-1} at the time of establishment.

The tea tree ecosystem located in Ningde, Eastern Fujian, covers two genotypes of tea planted in 1998, i.e., Oolong tea (designated 'OT') and green tea (designated 'GT'). Three field sites in each tea genotype plantation were established. Six field sites were established in the tea tree ecosystem used. These two tea plantations were managed using conventional cultivation techniques. The base fertilizer, including 4500 kg ha^{-1} manure and 750 kg ha^{-1} calcium superphosphate, were applied at establishment. Inorganic complex fertilizer (N:P:K 20:8:8) was applied at the rate of 3000 kg ha^{-1} yr^{-1} as additional fertilizer during three 15 cm-depth intertillage practices each year in March (50%), June (20%) and August (30%), respectively.

The fruit tree ecosystem located in Putian, Southern Fujian, includes two species of fruit trees planted in 1993, i.e. longan (Wulonglin, designated 'LW') and loquat (Zaozhong 6, designated 'LZ'). One field site in each fruit plantation was established. In total, two field sites were established in the fruit tree ecosystem. Both the 'LW' and 'LZ' plantation sites were fertilized additionally three times each year. The application rates of 180 kg N ha^{-1} yr^{-1}, 160 kg P_2O_5 ha^{-1} yr^{-1} and 225 kg K_2O ha^{-1} yr^{-1} were used in the 'LW' plantation site, spread over March (50%), June (20%) and September (30%) and the fertilizing rates in the 'LZ' plantation site were 360 kg N ha^{-1} yr^{-1}, 150 kg P_2O_5 ha^{-1} yr^{-1} and 270 kg K_2O ha^{-1} yr^{-1}, spread over February (20%), May (45%) and September (35%). In addition, chicken manure