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Asynchronous responses of soil carbon dioxide, nitrous oxide emissions and net nitrogen mineralization to enhanced fine root input

Xiaokang Hu [a], Lingli Liu [b], Biao Zhu [a], Enzai Du [a], Xueyang Hu [a], Peng Li [a], Zhang Zhou [a], Chengjun Ji [a], Jiangling Zhu [a], Haihua Shen [b], Jingyun Fang [a, b, *]

[a] Department of Ecology, College of Urban and Environmental Sciences, Key Laboratory for Earth Surface Processes of the Ministry of Education, Peking University, Beijing 100871, China
[b] State Key Laboratory of Vegetation and Environmental Change, Institute of Botany, Chinese Academy of Sciences, Beijing 100093, China

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ABSTRACT

Global environmental changes can remarkably alter the amount of fine root litter inputs to the soil; these inputs affect soil CO_2 and N_2O emissions and net N mineralization processes by changing C and N supply to microorganisms. However, how these C and N processes respond to the amount of fine root litter input is yet not known. In this study, a year-long incubation experiment was conducted to investigate the impacts of changes in fine root litter biomass input on soil respiration, N_2O emissions, and net N mineralization. Soil samples were obtained from forests of four biomes (boreal, temperate, subtropical, and tropical), and each sample was amended with fine roots from two species (either native tree species or maize roots) with four levels of root biomass input. The cumulative CO_2 emissions increased linearly with root input levels, regardless of soil and root litter types. Soil respiration responded strongly to root inputs within the first 100 days and then leveled off. Root inputs retarded soil N_2O emissions and net N mineralization, and the length of delay increased with root input levels, except for temperate and subtropical soils amended with tree roots, for which N_2O emission dynamics were not altered by root input. Tree roots retarded net N mineralization more intensively than maize roots except for the tropical tree roots. Cumulative N_2O emissions increased linearly with root input levels in only some soil type −root species−root input level combinations. Taken together, our results suggest that increased fine root biomass production might result in a linear increase of soil C loss via heterotrophic respiration, indicating that the first-order kinetic functions that have been widely used in the soil C models are still valid for predicting C mineralization rates in response to the changes in the amount of root litter inputs. Fine roots in their initial decomposition stage could be the predominant sources of soil N_2O emissions in some but not all terrestrial ecosystems. However, increased fine root input might retard net N mineralization, which might disrupt the temporal pattern of ecosystem N cycling, and thus have important consequences on plant N supply and growth.

1. Introduction

Soil respiration and net N mineralization are two crucial processes of the biogeochemical cycling of C and N. The feedback of soil respiration to global change is vital in modulating the global climate since soil respiration represents the largest single CO_2 source to the atmosphere, and small changes in soil respiration substantially influence CO_2 concentration in the atmosphere (Raich and Potter, 1995; Cox et al., 2000; Friedlingstein et al., 2006; Heimann and Reichstein, 2008). However, soil net N mineralization substantially affects C cycling because it controls the availability of N to plants, thereby determining plant growth and the amount of atmospheric C sequestrated by plants (Vitousek and Howarth, 1991; LeBauer and Treseder, 2008). Further, soil N mineralization provides the preliminary substrate (i.e., NH_4^+) for the production of nitrous oxide (N_2O), one of the three most important greenhouse gases in the atmosphere (Treut et al., 2007; Butterbach-Bahl et al., 2013), thereby rendering soil to be the most important source of the global N_2O budget (Ciais et al., 2013).

* Corresponding author. Department of Ecology, College of Urban and Environmental Sciences, Key Laboratory for Earth Surface Processes of the Ministry of Education, Peking University, Beijing 100871, China. Tel.: +86 10 6276 5578; fax: +86 10 6275 6560.
E-mail address: jyfang@urban.pku.edu.cn (J. Fang).

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Fine roots (diameter, <2 mm) play a key role in regulating soil C and N cycling (Hendricks et al., 1993; Rasse et al., 2005; Pregitzer et al., 2010). On a global scale, approximately 26–53% of plant-fixed C partitioned belowground is used for the production of fine root biomass, accounting for approximately 33% of the net primary productivity (NPP; Jackson et al., 1997; Litton and Giardina, 2008). The immense C pool of fine roots is an important source of soil organic carbon (SOC), which contributes about 2.4 times more than the aboveground litters for the formation of SOC (Rasse et al., 2005). Fine roots also actively control soil N cycling since the residence time of N in fine roots is about half of that in leaf litters (Pregitzer et al., 2010). The short residence time of N in fine roots along with the high C input through fine root biomass substantially affect soil C and N cycling via the interactions of C and N mineralization between fine roots and soil organic matter (Melillo et al., 1982; Berg and Laskowski, 2005; Kaiser et al., 2011). Furthermore, fine root biomass is known to be substantially influenced by global environmental changes; it can increase by 40–58%, 9–74%, and 24–46% due to atmospheric CO_2 enrichment (Norby and Zak, 2011), reactive N deposition (Liu and Greaver, 2010), and global warming (Lu et al., 2013), respectively.

However, our current understanding of the impacts of fine root decomposition and the increased fine root biomass on soil respiration, N_2O emissions, and N mineralization remains unclear. In soil C cycling models, soil respiration rate is generally represented as the first-order kinetic function of soil C pool size and the amount of plant material input (Parton et al., 1987; McGill, 1996). However, the input of plant materials represents labile substrate and energy sources to microorganisms, which can stimulate microbial growth and activities, thereby accelerating SOC mineralization and losses (Kuzyakov et al., 2000; Fontaine et al., 2007; Zhu and Cheng, 2011). Consequently, SOC mineralization might be underestimated by the current soil C cycling models that do not consider the effect of the stimulation of SOC loss by plant materials (Fontaine et al., 2007; Sayer et al., 2011). Although many studies have investigated the effects of plant material input on SOC mineralization, many aspects yet remain unclear (Kuzyakov, 2011). For example, in many field litter manipulation studies, the amount of plant material inputs were limited to two or three levels due to methodological constraints and high labor demand, thereby limiting the ability to predict the response of SOC mineralization to the amount of plant material input (Sayer, 2006; Leff et al., 2012; Xu et al., 2013). Only one field study with more than three levels of litter inputs indicated that soil respiration rate increased linearly with the amount of grass litter input (Xiao et al., 2015). However, of the two laboratory incubation studies performed using plant materials with more than three levels of inputs, only one showed that soil respiration rate increased linearly with plant material input (Liu et al., 2009; Guenet et al., 2010).

The impacts of plant material input on soil respiration have been widely investigated; however, its effect on soil N_2O emission and net N mineralization has not been studied extensively (Xu et al., 2013). Generally, C content in decomposing litter decreases monotonously, whereas the N content increases initially and then decreases over the course of decomposition (Melillo et al., 1982; Parton et al., 2007), indicating that decomposing litter might have a substantial impact on soil net N mineralization because the additional N enrichment of decomposing litter is initially transferred from soils by microbes (Frey et al., 2003). Decomposing plant litter is known to be an intensive "hot-spot" of net N mineralization and N_2O emissions in soils, which occur at considerably higher levels in litter than in bulk soil (Parkin, 1987; Hesselsøe et al., 2001). Therefore, understanding the effects of fine root decomposition and increased fine root biomass input on soil N_2O emissions and net N mineralization is crucial for further elucidating the interactions between C and N cycling and N_2O emission in terrestrial ecosystems (Thomas et al., 2013).

This study aimed to investigate the impacts of increased fine root input on soil respiration, N_2O emissions, and net N mineralization during root decomposition. To this end, a one-year incubation experiment was conducted with four distinct soil types. We hypothesized that (I) cumulative CO_2 and N_2O emissions would increase linearly with fine root input levels since the decomposing roots might be the dominant CO_2 and N_2O sources of the entire soil system; (II) maize roots impact soil respiration, N_2O emissions, and net N mineralization dynamics more intensively than tree roots due to their higher quality; and (III) soil type substantially affects the response of soil respiration, N_2O emissions, and net N mineralization to root addition owing to their distinct physical, chemical, and biological properties.

2. Materials and methods

2.1. Soil and fine root collection, preparation, and analyses

Primary forests that belong to four distinct biomes were selected for soil and fine root collection; the vegetation type of the sampling sites was representative for each region (Table 1). Subsoil (10–30 cm) was used for incubation because fine root biomass production in the subsoil is known to be influenced more remarkably than that in the topsoil (Iversen, 2010; Norby and Zak, 2011). Further, subsoil contains less plant materials (both living roots and dead decomposing litters) than topsoil (0–10 cm), especially in the boreal forest where the topsoil is organic layer and contains numerous roots and litters at different decomposing stages (Table 3). Using subsoil facilitates the process of removing plant materials from the soil, which can minimize the influence of residual plant materials in the soil on the effects of added roots. For each forest type, soils (equal weight) were collected from four locations, and the four soil samples were pooled and mixed evenly to obtain one soil sample. After all gravel, biochar, and roots that were visible to the naked eye were carefully removed, soil samples were stored at 4 °C until incubation. The soil samples were pre-incubated at 25 °C and maintained at 60% water holding capacity (WHC) for one week. For fine root collection, *Larix gmelinii* (Rupr.) Kuzen, *Quercus liaotungensis* Koidz, and *Castanopsis eyrei* (Champ.) Tutch from boreal, temperate, and subtropical sites, respectively, were selected, because they are the most abundant tree species. For the tropical site, *Cryptocarya chinensis* (Hance) Hemsl (one of the dominant tree species) was selected because distinguishing its fine roots from those of other species was easier in this complex tropical rainforest. Maize (*Zea mays* L.) roots were collected from an agricultural field at Quzhou County, Hebei (36°52′N, 115°10′E). Fine roots were rinsed and oven-dried at 50 °C for 72 h. Soil WHC was determined according to the method described by Paul et al. (2001). Soil texture was estimated following the United States Department of Agriculture textural triangle. Soil pH (1:2.5 in soil:water w/v ratio) was measured using a pH meter (PB-10; Sartorius, Germany). Cation exchange capacity was measured using buffered NH_4OAc, and soil C and N contents were measured using a CHNOS elemental analyzer (Vario EL III; Elementar Analysensysteme GmbH, Germany).

2.2. Microcosm and treatment design

Microcosms were constructed using 450-mL Mason jars equipped with modified plastic lids with a hole (diameter = 6 mm) in the center to ventilate headspace air and retard soil water loss. With these modified lids, the jar headspace CO_2 concentration never exceeded 1% throughout the incubation. Within each jar,