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Concentration and mineralization of organic carbon in forest soils along a climatic gradient

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ABSTRACT

Forty-four percent of the organic carbon (OC) in the world's forests is stored in soils. However, the distribution and stability of OC in forest soils along a climatic gradient remain largely unclear, hindering our understanding and the accurate prediction of biogeochemical cycles in forest ecosystems in a changing world. To address these uncertainties, we measured OC and nitrogen (N) concentrations and mineralization of OC in soils from broadleaved and coniferous forests along a wide-ranging climatic gradient in China and related these to experimental N addition and climatic conditions. An 85-day incubation was conducted under 25 °C and 60% of soil moisture at field capacity to determine the mineralization of soil OC. We hypothesized that the concentrations of OC and N would be higher but the mineralization of OC would be lower in soils from colder and drier forests and that the mineralization would be positively responsive to N addition. In support of these hypotheses, the concentrations of OC and N decreased, while the mineralization of OC measured under standard laboratory condition increased, with mean annual precipitation (MAP) and temperature (MAT). These metrics were not affected by forest type or the interaction between forest type and site. Nitrogen addition increased the cumulative mineralized OC (C_m, g kg^{-1}) by 6–67%, and the effects varied with site and soil depth, but were similar between the broadleaved and coniferous forests. The C_m decreased with increasing soil OC concentration, C/N ratio and mineral N, while the rate constant of OC mineralization (k, day^{-1}) showed opposite relationships with these metrics. The addition of N did not change the slopes of the relationships of C_m and k with the C/N ratio, MAP, and MAT; however, it strengthened the negative relationship of C_m with OC and mineral N concentrations. The results from this study suggested that the mineralization of OC was limited by N availability in the studied forested soils, and the response of OC mineralization to N addition was independent of climatic conditions.

1. Introduction

Forty-four percent of the organic carbon (OC) in the world's forests is stored in the soil (Pan et al., 2011). Forest soils play an important role in regulating the response of global biogeochemical cycles to anthropogenic disturbance and global change (Hadden and Grelle, 2016; Keenan et al., 2014; Seidl et al., 2014). Therefore, understanding the distribution and stability of OC in forest soils along a climatic gradient would provide essential information for predicting OC dynamics at regional to global scales.

The stability of soil OC is often assessed by measuring the metrics of mineralization or decomposition of soil organic matter, in which a lower mineralization rate represents a higher stability (Fang et al., 2005; Fontaine et al., 2007; Schmidt et al., 2011). The mineralization of soil OC is usually determined by measuring CO_2 emissions during controlled incubation of soil samples at certain conditions (Fang et al., 2005; Fontaine et al., 2007; Schmidt et al., 2011; Cotrufo et al., 2015; Jenny et al., 1949; Karhu et al., 2010; Knorr et al., 2005; Powlson et al., 1987). As an important factor in land management, nitrogen (N) supply significantly affects OC mineralization by influencing the chemical properties of soil, microbial and enzymatic activities, and the quantity and availability of substrates (Hobbie, 2008; Leifeld et al., 2008; Min et al., 2011). The mineralization of OC in soils, however, responds inconsistently to N addition, with previous reports of increased (Menyailo et al., 2014; Tu et al., 2013) or decreased (Min et al., 2011; Tonitto et al., 2014) mineralization following N addition. This inconsistency

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may be a result of differences in the quality of the organic matter and soil properties (Du et al., 2014; Knorr et al., 2005; Leifeld et al., 2008), all of which greatly vary among sites and climatic conditions. Moreover, OC mineralization is highly dependent on climatic conditions (Doetterl et al., 2015; Fissore et al., 2008; Homann et al., 2007), but whether such dependence is affected by N addition or whether the response of OC mineralization to N addition is affected by climate remains untested in both observational and experimental studies. These uncertainties limit our understanding of the responses of ecosystems to global change and emphasize the need for further studies on the effects of N addition on OC stability in forest soils along climatic gradients.

The forest type is also an important factor that contributes to variations in soil OC cycling by affecting the quality and quantity of fresh litter or root inputs and thus controlling the composition and biodegradability of organic matter in soils (Augusto et al., 2015; Cools et al., 2014; Mueller et al., 2012; Reich et al., 1997). Coniferous needles generally have more recalcitrant carbon components than the leaves of broadleaved trees (Shirato and Yokozawa, 2006), resulting in different OC mineralization rates and various coupled relationships between OC cycling in forest soils (Quan et al., 2014). No consensus has yet been reached on the effects of forest type on OC mineralization in soils. For example, the mineralization of soil OC has been reported to be higher (Mueller et al., 2012; Reich et al., 1997; Xu et al., 2014) or similar (Augusto et al., 2015; Colman and Schimel, 2013; Mueller et al., 2012) in broadleaved forests compared to coniferous forests, including not only unexplained variability but also some variability contingent on whether mineral soil or organic horizons were measured, or on whether natural or plantation stands were compared. This range of observations provides some understanding of the effect of forest type on OC dynamics but highlights the uncertainty in such response, hindering the extrapolation of these results to a larger spatial scale and the identification of a universal pattern of influences.

In this study, we hypothesized that (H1) the concentrations of OC and N, and the mineralization of OC under standard temperature and soil moisture condition would be higher in broadleaved forests compared to those in coniferous forests, that (H2) the concentrations of OC and N would be higher but the mineralization under standard conditions lower in soils from colder and drier forests, and that (H3) the mineralization of OC under standard conditions would be positively responsive to N addition because most forests are limited by N availability. To test these hypotheses, we collected mineral soils from coniferous and broadleaved forests at 11 sites in China. These sites were located throughout China across a wide range of climatic gradient, which determines soil texture, the concentrations of OC and N, and the quality of soil organic matter. All these factors can directly affect soil OC mineralization. We measured the OC concentration and mineralization at a commonly used standard temperature (25 °C) and soil moisture (60% field capacity) condition. The effects of N addition and dependence on climatic conditions were also examined.

2. Materials and methods

2.1. Study sites and soil sampling

Soil samples were collected from 11 forested sites in China along a 22 °C gradient of mean annual temperature (MAT) and a 2000 mm gradient of mean annual precipitation (MAP) (Table 1, Fig. 1). Climatic data were available for all sites. Two adjacent tracts of broadleaved and coniferous forest stands were selected as replicates at two subsites (~3 km apart) at each site, except for Helan and Xishuangbanna, where only coniferous or broadleaved forest was selected. The age of the dominant species in our forest was over 80 years, which is considered as the mature forest (Keeton et al., 2007; Liu et al., 2014). The dominant species of each forest type at each site are shown in Table 1. Three plots (20×20 m in size) were established > 100 m apart in each adjacent tract of each forest. The plots in each forest had the same soil type and

Table 1
Description of each site used in this study along a climatic gradient in China.

# Site	Location	Province	MAP (mm)	MAT (°C)	Soil types	Sampling depth	Forest types and dominant species	
							Broadleaved forest	Coniferous forest
1	Helan	Ningxia	300	3.5	Alfisols	0–10 cm, 10–20 cm		*Picea crassifolia, Pinus tabuliformis, Juniperus rigda*
2	Beijing	Beijing	575	7.5	Alfisols	0–10 cm, 10–20 cm	*Populus davidiana, Betula platyphylla Suk, Quercus liaotungensis*	*Pinus tabuliformis, Larix principis-rupprechtii*
3	Huanglong	Shaanxi	611.8	8.6	Inceptisols	0–10 cm, 10–20 cm	*Betula platyphylla Suk, Quercus liaotungensis*	*Pinus tabuliformis*
4	Guyuan	Ningxia	676	5.8	Alfisols	0–10 cm, 10–20 cm	*Betula platyphylla Suk, Quercus liaotungensis*	*Pinus armandi, Larix principis-rupprechtii*
5	Harbin	Heilongjiang	723.8	2.8	Alfisols	0–10 cm, 10–20 cm	*Betula platyphylla Suk*	*Pinus koraiensis Sieb. et Zucc.*
6	Bijie	Guizhou	877	13	Inceptisols	0–10 cm	*Castanopsis Spach, Populus davidiana, Cinnamomum parthenoxylon (Jack) Nees*	*Cunninghamia lanceocycla Mitf, Pinus yunnanensis, Keteleeria davidiana (Bertr.) Beissn*
7	Changsha	Hunan	1422	17	Ultisols	0–10 cm, 10–20 cm	*Liquidambar formosana Hance, Cinnamomum camphora*	*Pinus massoniana, Cunninghamia lanceocycla Mitf*
8	Taihe	Jiangxi	1726	17.8	Ultisols	0–10 cm, 10–20 cm	*Schima superba*	*Pinus massoniana, Cunninghamia lanceocycla Mitf*
9	Xishuangbanna	Yunnan	1795	19	Ultisols	0–10 cm, 10–20 cm	*Dysoxylum excelsum Bl, Pometia pinnata, Pittosporopsis kerrii Craib*	
10	Wuyishan	Fujian	1800	16	Ultisols	0–10 cm, 10–20 cm	*Idesia polycarpa, Castanopsis fargesii*	*Cunninghamia lanceolata Pinus tanwanensis*
11	Wuzhishan	Hainan	2419	22.5	Ultisols	0–10 cm, 10–20 cm	*Lithocarpus fenzelianus, Castanopsis tonkinensis*	*Pinus fenzeliana, Keteleeria hainanensis,*

Soil was classified according to Soil Survey Staff in USDA (1992).