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Mean residence time of global topsoil organic carbon depends on temperature, precipitation and soil nitrogen

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ABSTRACT

Mean residence time (MRT) of topsoil organic carbon is one critical parameter for predicting future land carbon sink dynamics. Large uncertainties remain about controls on the variability in global MRT of soil organic carbon. We estimated global MRT of topsoil (0–20 cm) organic carbon in terrestrial ecosystems and found that mean annual air temperature, annual precipitation, and topsoil nitrogen storage were responsible for the variability in MRT. An empirical climate and soil nitrogen-based (Clim&SN) model could be used to explain the temporal and spatial variability in MRT across various ecosystems. Estimated MRT was lowest in the low-latitude zones, and increased toward high-latitude zones. Global MRT of topsoil organic carbon showed a significant declining tendency between 1960 and 2008, particularly in the high-latitude zone of the northern hemisphere. The largest absolute and relative changes (0.2% per yr) in MRT of topsoil organic carbon from 1960 to 2008 occurred in high-latitude regions, consistent with large carbon stocks in, and greater degree of climate change being experienced by, these areas. Overall, global MRT anomalies (differences between MRT in each year and averaged value of MRT from 1960 to 2008) of terrestrial topsoil organic carbon were decreasing from 1960 to 2008. Global MRT anomalies decreased significantly ($P<0.001$) with the increase of global temperature anomalies, indicating that global warming resulted in faster turnover rates of topsoil organic carbon.

1. Introduction

Topsoil is the component of the soil that shows the most rapid response to global change and/or management effects and other human disturbance. Topsoil at 0–20 cm is consistently sampled in soil organic carbon storage surveys or soil fertility monitoring. Mean residence time (MRT) of topsoil organic carbon is one critical parameter for predicting future land carbon sink dynamics. The variation of topsoil carbon stock accounts for 80%–90% of the stock variations observed over decades (Liao et al., 2009).

Factors influencing soil carbon MRT are hotly debated. For example, experimental studies indicated increased organic carbon decomposition (Jenkinson and Ayanaba, 1977; Lloyd and Taylor, 1994; Trumbore et al., 1996; Kätterer et al., 1998; Holland et al., 2000; Dalias et al., 2001; Sanderman et al., 2003) at higher temperatures, resulting in increased CO_2 emissions from soils. However, Giardina and Ryan (2002) questioned whether turnover times of soil carbon depended on temperature. Davidson et al. (2000) suggested that soil temperature, moisture and other factors interacted to influence decomposition of organic carbon. Most importantly, ecosystem processes and attributes affecting soil carbon turnover across ecosystems may reflect the interactions between numerous environmental factors such as climate, and soil. Some previous investigations have emphasized the importance of climatic controls on soil organic carbon turnover (Sanderman et al., 2003). Few studies focused on the relationship between MRT of organic carbon and soil conditions, such as nitrogen content. Nitrogen-induced changes in microbial community structure or function could affect the decomposition of soil organic carbon. Sinsabaugh et al. (2005) proposed that soil nitrogen differentially affected the microbial degradation of polysaccharides and polyphenols, resulting in an uncoupling of these processes. Greater nitrogen availability could inhibit the degradation of lignin and its derivatives due to lowered oxidative enzyme activity, which might result in an accumulation of lignin derivatives in soil (Grandy et al., 2008). In addition, nitrogen addition may increase soil carbon residence time by reducing heterotrophic soil respiration (Janssens et al., 2010). Because the key factors controlling MRT of topsoil organic carbon are not well characterized, the spatial and temporal variability in global MRT remains largely unknown.

In this study, we investigated the effects of mean annual air temperature, annual precipitation and soil properties on MRT of topsoil organic carbon. Meaningful cross-site comparisons of MRT require stocks of organic carbon to be reported by constant depth intervals. We, here, are referring to carbon stored down 20 cm from the top of the O horizon (top organic layer of soil), if any, to A horizon (mineral layer). And the

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topsoil organic carbon is abbreviated as SOC. This criterion is consistent within the data sets used in our study. Using an empirically based model including climate and soil factors we identified key properties responsible for global variability in MRT of SOC. We aimed to characterize the spatial and temporal variability in global MRT of SOC. This work will add to our understanding of variability in global SOC dynamics and controls.

2. Material and methods

2.1. Data sets

Sites including both topsoil (0–20 cm) organic carbon storage and annual soil respiration measurements were compiled in our data sets across global terrestrial ecosystems. Measurement sites distributed from 37°31′S to 67°72′N latitude and from 155°15′W to 149°10′E longitude, which cover most of ecosystem types and climate zones over the world (Fig. 1; Chen et al., 2010). We compiled annual heterotrophic and soil respiration data which were simultaneously measured in sites (see Table A.1 in Supplementary materials). The data sets also included annual precipitation, mean annual temperature and relevant soil (0–20 cm) properties (see Table A.2 in Supplementary materials). Here, soil properties included total nitrogen storage, pH, bulk density, clay content and sand content (see Table A.2 in Supplementary materials). In the present data sets, soil nitrogen and pH are available for most measurement sites. Not much data on bulk density, clay content and sand content are available in the published literatures.

2.2. Data processing and analyzing

The MRT of SOC was estimated by dividing the mass of organic carbon in the top 20 cm of the soil profile by the soil heterotrophic respiration rate (Raich and Schlesinger, 1992; Mcculley et al., 2004; Smith and Johnson, 2004; Garten and Hanson, 2006):

$$MRT = SOC/R_h \tag{1}$$

Where MRT is the mean residence time (yr) of topsoil organic carbon, SOC is topsoil (0–20 cm) organic carbon storage (kg C m^{-2}), and R_h is the heterotrophic respiration rate (kg C m^{-2} yr^{-1}). Here, heterotrophic respiration rate was estimated by using the compiled global data sets of soil respiration and its heterotrophic subcomponent (see Fig. A.1, Table A.1 and Table A.2 in Supplementary materials). The relationship between heterotrophic respiration and soil respiration can be described by the following function:

$$R_h = e^{(0.88\ln(R)+0.20)} \tag{2}$$

Where R is total soil respiration rate (kg C m^{-2} yr^{-1}). In order to evaluate and validate the accuracy of predicted R_h, we also compared the estimated values to those based on the functions provided by Bond-Lamberty and Thomson (2010a, 2010b) (Eq. (3)) and Bond-Lamberty et al. (2004) (Eq. (4)):

$$R_h = e^{(0.87\ln(R)+0.22)} \tag{3}$$

$$R_h = e^{(0.73\ln(R)+1.22)} \tag{4}$$

The calculated MRT value for each measurement site was used for regression analysis and modeling. We conducted a pairwise (Pearson product–momentum) correlation for each pair of variables including compiled data on MRT of SOC, annual precipitation, annual mean air temperature, and soil properties (total nitrogen storage, pH, bulk density, clay content and sand content) (Table 1). Four aspects were

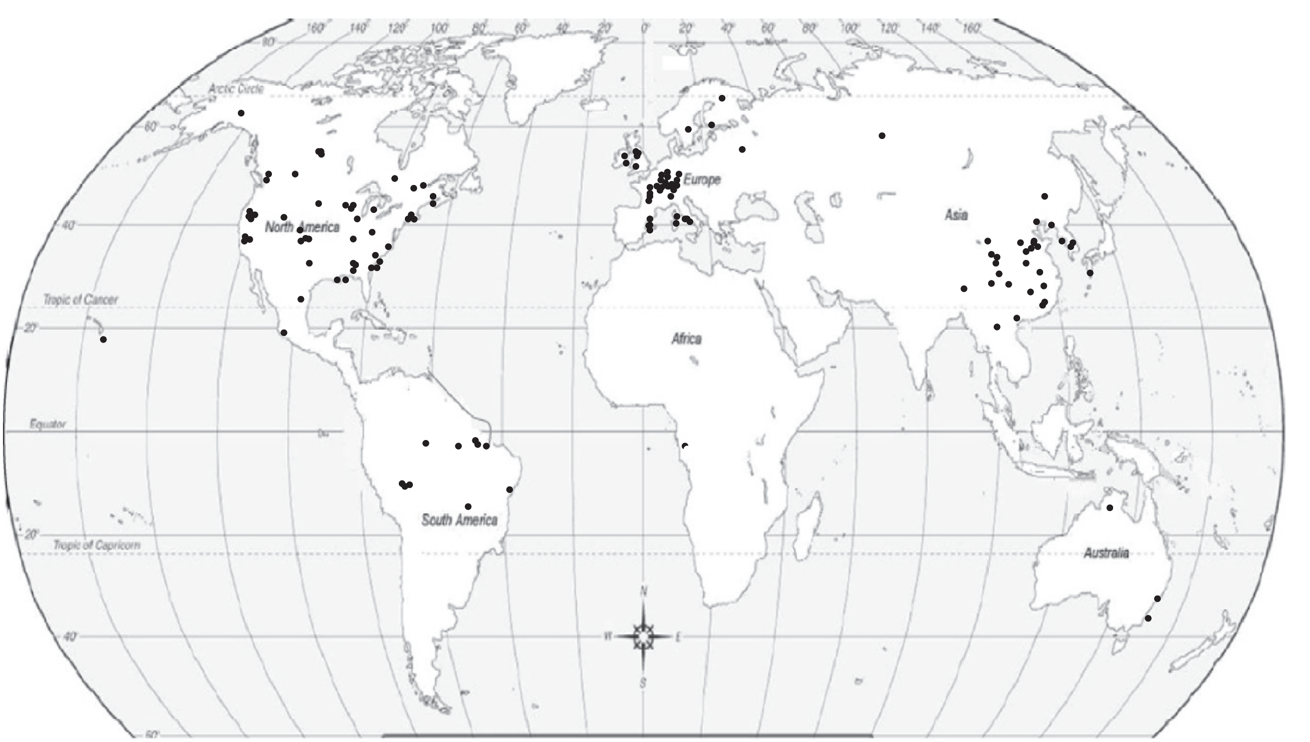

Fig. 1. Geographical distribution of field measurement sites. These measurements were compiled in the data sets in Table A.1 and Table A.2. Data on annual soil respiration, annual total precipitation and mean air temperature exist for each of these sites. Soil carbon, nitrogen and heterotrophic respiration are not available for all sites. The detailed information for each site can also be found in Table A.1 and Table A.2.