Agricultural and Forest Meteorology 263 (2018) 137–146

Contents lists available at ScienceDirect

Agricultural and Forest Meteorology

journal homepage: www.elsevier.com/locate/agrformet

Warming exerts greater impacts on subsoil than topsoil CO_2 efflux in a subtropical forest

Weisheng Lin[a], Yiqing Li[a,b], Zhijie Yang[a], Christian P. Giardina[c], Jinsheng Xie[a], Shidong Chen[a], Chengfang Lin[a,*], Yakov Kuzyakov[d,e,f], Yusheng Yang[a,*]

[a] Key Laboratory for Subtropical Mountain Ecology (Ministry of Science and Technology and Fujian Province Funded), School of Geographical Sciences, Fujian Normal University, Fuzhou 350007, China

[b] College of Agriculture, Forestry and Natural Resource Management, University of Hawaii, Hilo, HI, 96720, USA

[c] Institute of Pacific Islands Forestry, Pacific Southwest Research Station, USDA Forest Service, Hilo, HI, 96720, USA

[d] Department of Soil Science of Temperate Ecosystems, Department of Agricultural Soil Science, University of Göttingen, 37077 Göttingen, Germany

[e] Institute of Physicochemical and Biological Problems in Soil Science, Russian Academy of Sciences, 142290 Pushchino, Russia

[f] Soil Science Consulting, 37077 Gottingen, Germany

ARTICLE INFO

Keywords:
Chinese fir
CO_2 flux
Fine root
Manipulative warming
Soil moisture
Soil temperature
Subtropical plantation

ABSTRACT

How warming affects the magnitude of CO_2 fluxes within the soil profile remains an important question, with implications for modeling the response of ecosystem carbon balance to changing climate. Information on belowground responses to warming is especially limited for the tropics and subtropics because the majority of manipulative studies have been conducted in temperate and boreal regions. We examined how artificial warming affected CO_2 gas production and exchange across soil profiles in a replicated mesocosms experiment relying on heavily weathered subtropical soils and planted with Chinese fir (*Cunninghamia lanceolata*). Half of 2 × 2 m mesocosms (5 replications) was heated with cables buried at a 10 cm depth, which increased temperature in the whole soil profile by 4.5, 3.6 and 2.5 °C at 15, 30 and 60 cm soil depths, respectively. Using a combination of chamber-based and concentration gradient method (CGM) approaches, we found that warming increased soil CO_2 efflux across the whole profile by 40%. Changes were unevenly distributed across soil depth: mean CO_2 production rate decreased from 0.74 to 0.67 μmol CO_2 m^{-2} s^{-1} in topsoils (0–15 cm depth) whereas it increased from 0.26 to 0.73 μmol CO_2 m^{-2} s^{-1} in subsoils (15–60 cm depth). Warming reduced moisture more strongly in subsurface than surface soils and increased subsoil soluble N concentrations as well as fine root turnover, in line with previous temperate and boreal warming studies. This consistency indicates that overall responses of subtropical forests to warming may be similar to forests in higher latitudes.

1. Introduction

Small changes in the global balance of C inputs to and losses from soil can exert a significant influence on atmospheric [CO_2]. However, there is significant uncertainty about temperature controls on the loss term in the soil C storage equation (Giardina et al., 2014; Bradford et al., 2016; Jackson et al., 2017), in part because our understanding of soil C formation and subsequent decomposition is poor. This uncertainty is particularly strong for tropical and subtropical forests (Piao et al., 2013; Cavaleri et al., 2015; van Gestel et al., 2018). Efforts directed at understanding the response of C process rates to change, particularly in deeper soil horizons, is critical to reducing this uncertainty (Rumpel and Kögel-Knabner, 2011). Despite occurring at relatively low concentrations, total C stored below 20 cm accounts for more than 50% of the world's soil organic carbon (SOC) (Jobbágy and Jackson, 2000; Jackson et al., 2017). Therefore, even small changes in belowground process rates could play a significant role in shaping the CO_2 source or sink strength of the atmosphere.

The potential mechanisms for subsoil C stability can be summarized as follows: C input into subsoils is derived by plant roots or/and the microbial decomposition products of plant litters (Kuzyakov and Blagodatskaya, 2015; Giardina et al., 2014), both of which can be chemically more resistant to decomposition than fresh litter on the soil surface (Nierop, 1998; Lorenz and Lal, 2005; Rumpel and Kögel-Knabner, 2011). In addition, the transport of enzymes, substrates, water, oxygen and microorganisms is limited in deeper parts of the soil profile (Rumpel and Kögel-Knabner, 2011), which can contribute to a spatial separation of microbes and C inputs, which slows the turnover of

* Corresponding author.
E-mail addresses: Tonylcf99@163.com (C. Lin), geoyys@fjnu.edu.cn (Y. Yang).

https://doi.org/10.1016/j.agrformet.2018.08.014
Received 27 January 2018; Received in revised form 19 August 2018; Accepted 20 August 2018

deep soil C (Lützow et al., 2006; Holden and Fierer, 2005). Similarly, Lützow et al. (2006) and Schmidt et al. (2011) argue that biotic and abiotic environmental factors are more important than C quality in determining C stability in deep soil.

Dozens of field experiments and laboratory incubation studies in temperate and boreal zones have documented positive soil organic matter (SOM) decomposition responses to warming, as well as increases in the concentrations of dissolved organic carbon (DOC) and NO_3^- availability caused by experimental warming, which can accelerate C and N leaching to deeper soil (Lu et al., 2013; Bai et al., 2013; Crowther et al., 2016). Warming-induced declines in soil moisture can increase gas diffusivity, enhance root growth but also increase root mortality in the soil profile (Lu et al., 2013; Yang et al., 2013). The extent to which these observed responses to warming also characterize responses in the tropics is unknown.

South China has a monsoonal climate, and the climax vegetation of this region is subtropical evergreen broadleaved forest developed on highly weathered soils (Huang et al., 2013). Due to increasing demand for timber and other forest products over the past several decades, most native broadleaved forests have been harvested, and were subsequently converted to plantations of more productive tree species, especially Chinese fir (*Cunninghamia lanceolata*) (Yang et al., 2009), which now covers over 9 million ha and accounts for 30% of all plantations in China (Lei, 2005). To understand how global warming will affect ecosystem C balance in the tropics, we established a soil warming mesocosm experiment in Fujian Province, China (Liu et al., 2017). We planted this experiment with Chinese fir because of its widespread use across the region as a premier plantation species. We selected a heavily weathered soil typical of subtropical plantation forests in south China, and broadly representative of tropical forest soils. Building on previous work at this site (Liu et al., 2017), we used these replicated mesocosms to examine vertical CO_2 fluxes from subsurface and surface soils as well as efflux at the soil surface. To understand the mechanisms involved in the CO_2 fluxes across soil profiles, we examined *in-situ* soil moisture, temperature, nutrients, DOC and fine roots (Fierer et al., 2003).

We hypothesized that soil warming increases: (1) CO_2 production rates, with proportionally higher contribution to CO_2 production in subsoil due to enhanced microbial activities and root growth (Fontaine et al., 2007); (2) fine root turnover rate and distribution in subsoil where warming reduces water availability (Hendrick and Pregitzer, 1996; Hutchings and John, 2003); and (3) DOC concentrations and N availability in subsoil because of enhanced mortality rates for fine roots, and warming-induced N leaching (Lu et al., 2013; Yang et al., 2013).

2. Materials and methods

2.1. Research area description

This study was conducted in the Chenda Observation Study Site of Sanming Forest Ecosystem and Global Change Research Station (26°19′3″ N, 117°36′22″ E, 300 m a.s.l) in Fujian Province with 66% of forest cover. Native forest vegetation in this region is dominated by evergreen broadleaf species, the majority of which are in the Fagaceae family. The Sanming Research Station is characterized by a typical maritime subtropical monsoon climate with a mean annual temperature (MAT) of 19.1 °C. Temperature extremes occur in January (mean monthly temperature of 9.7 °C) and in July (mean monthly temperature of 28.2 °C). Mean relative humidity, mean annual precipitation (MAP) and mean annual potential evapotranspiration are 81%, 1750 mm and 1585 mm, respectively. Precipitation from March to August accounts for > 70% of the total annual precipitation. Soils at the site are classified as red soils according to China's soil classification categories equivalent to Oxisols in USDA soil taxonomy (State Soil Survey Service of China, 1998; Soil Survey Staff of USDA, 2014).

2.2. Experimental design

Details of the experimental design have been previously reported (Liu et al., 2017, but briefly we established a mesocosm warming experiment in August 2013. Five control and five warming 2 m × 2 m plots were established, with PVC boards (0.8 cm thick) inserted to a depth of 70 cm to separate plots from adjacent plots and surrounding soil. Subsequently, heating cables (TXLP/1, Nexans, Norway) contained a resistance wire with an output of 17 W m^{-1} at 230 V were installed at a soil depth of 10 cm. The distance between cables was 20 cm. Temperature increase of 5.0 °C was targeted based on the RCP 8.5 scenario's prediction and the information that majority of studies in the temperate and boreal forests used 3–7 °C increase as warming treatment (Bronson et al., 2008; Melillo et al., 2002). Soil temperature sensors (T109 from Campbell Scientific Inc., Logan, UT, USA) were placed between two cable lines (6 m long per square meter) at a soil depth of 10 cm in each plot. Three temperature sensors were installed in each warming plot and two in each control plot. Soil moisture for 0–10 cm soil layer was measured with 2 ECH2O-5 soil moisture probes (Decagon, Pullman, Washington, USA). Soil temperature and moisture were recorded at 30-minute intervals.

In November 2013, four one-year-old Chinese-fir seedlings were planted in each plot between the cables. The 40 Chinese-fir seedlings were carefully selected from more than 1000 seedlings to minimize variability in height, basal diameter, and size of the root system. Based on previous work with this species, the Chinese-fir seedlings grew normally after planting. Warming started on March 1, 2014 and data were not collected until May of 2014.

2.3. Soil CO_2 gas concentration measurements

Soil gas from different depths was sampled using gas wells (Breecker et al., 2012; Maier and Schack-Kirchner, 2014; Oerter and Amundson, 2016). Three sampling tubes (DIK-5212, Japan) were installed vertically at the depths of 15, 30 and 60 cm in each plot in March 2014. Once installed, each sampling tube was sealed to gases other than those diffusing in from the soil layer being sampled. A medical syringe was connected to the three-way cock valve when sampling the soil gas. The syringe piston was retracted slowly to reduce soil disturbance, and to ensure gas sample integrity (Hashimoto et al., 2007; Maier and Schack-Kirchner, 2014). Soil gas was sampled biweekly using a syringe from May 2014 to May 2015. The collected soil gas was injected into a gas bag (Delin, China) and immediately sent to the laboratory to determine CO_2 concentration with gas chromatography (Shimadzu gas chromatograph, Japan).

In each plot, three multifunction sensors (5TE, Decagon Devices Inc., USA) were installed next to the gas sampling tubes and connected with a self-contained digital data logger (EM50, Decagon Devices Inc., USA) to measure soil temperature and moisture at depths of 0–20, 20–40 and 40–60 cm at an interval of 30 min.

2.4. Soil CO_2 production calculation and validation

In this study, the flux of CO_2 diffused through each layer was calculated from D_s and the discrete difference in the CO_2 concentration across each layer according to Fick's first law of diffusion:

$$F_S = -D_s \frac{\Delta C(z)}{\Delta z} \quad (1)$$

Where F_s is the CO_2 efflux (μmol m^{-2} s^{-1}), D_s is the CO_2 diffusion coefficient in the soil (m^2 s^{-1}), C is the CO_2 concentration (μmol m^{-3}) at soil depth of z (m), and $\frac{\Delta C(z)}{\Delta z}$ is the vertical soil CO_2 gradient. D_s was estimated as

$$D_s = \xi D_a \quad (2)$$

Where ξ is the gas tortuosity factor, and D_a is the CO_2 diffusion