Soil Biology & Biochemistry 42 (2010) 576–585

Contents lists available at ScienceDirect

Soil Biology & Biochemistry

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

Factors controlling soil CO_2 effluxes and the effects of rewetting on effluxes in adjacent deciduous, coniferous, and mixed forests in Korea

Dong-Gill Kim [a], Shouguo Mu [a,c], Sinkyu Kang [b], Dowon Lee [a,*]

[a] Graduate School of Environmental Studies, Seoul National University, Seoul 151-742, Republic of Korea
[b] Department of Environmental Science, Kangwon National University, Chuncheon, Kangwon-do 200-701, Republic of Korea
[c] School of Environment Science & Spatial Informatics, China University of Mining and Technology, Xuzhou 221008, China

ARTICLE INFO

Article history:
Received 16 August 2009
Received in revised form
11 November 2009
Accepted 8 December 2009
Available online 4 January 2010

Keywords:
Soil CO_2 efflux
Control factor
Rewetting
Peak emission
Deciduous forest
Coniferous forest
Mixed forest

ABSTRACT

To better understand the factors that control forest soil CO_2 efflux and the effects of rewetting on efflux, we measured soil CO_2 efflux in adjacent deciduous, coniferous, and mixed forests in the central part of the Korean Peninsula over the course of one year. We also conducted laboratory rewetting experiments with soil collected from the three sites using three different incubation temperatures (4 °C, 10 °C, and 20 °C). Soil moisture (SM), soil organic matter (SOM), and total root mass values of the three sites were significantly different from one another; however, soil temperature (ST), observed soil CO_2 efflux and sensitivity of soil CO_2 efflux to ST (i.e., $Q_{10} = 3.7 \pm 0.1$) were not significantly different among the three sites. Soil temperature was a dominant control factor regulating soil CO_2 efflux during most of the year. We infer that soil CO_2 efflux was not significantly different among the sites due to similar ST and Q_{10}. Though a significant increase in soil CO_2 efflux following rewetting of dry soil was observed both in the field observations (60–170%) and laboratory incubation experiments (100–1000%), both the increased rates of soil CO_2 efflux and the magnitude of change in SM were not significantly different among the sites. The increased rates of soil CO_2 efflux following rewetting depended on the initial SM before rewetting. During drying phase after rewetting, a significant correlation between SM and soil CO_2 efflux was found, but the effect of ST on increased soil CO_2 efflux was not clear. Cumulative peak soil CO_2 efflux (11.3 ± 0.7 g CO_2 m^{-2}) following rewetting in the field was not significantly different among the sites. Those evidences indicate that the observed similar rewetting effects on soil CO_2 efflux can be explained by the similar magnitude of change in SM after rewetting at the sites. We conclude that regardless of vegetation type, soil CO_2 efflux and the effect of rewetting on soil CO_2 efflux do not differ among the sites, and ST is a primary control factor for soil CO_2 efflux while SM modulates the effect of rewetting on soil CO_2 efflux. Further studies are needed to quantify and incorporate relationship of initial dryness of the soil and the frequency of the dry–wet cycle on soil CO_2 efflux into models describing carbon (C) processes in forested ecosystems.

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1. Introduction

The increase in atmospheric CO_2 concentration has motivated efforts to understand how global carbon pools respond to environmental changes. Soils play an important role in the global carbon (C) cycle, as they are the dominant terrestrial source of CO_2 (Forster et al., 2007). Carbon dioxide is produced in soil by heterotrophic (decomposer organisms) and autotrophic (living roots and mycorrhizae) activity, and most of this CO_2 is released to the atmosphere. This process, commonly called soil CO_2 efflux, produces 75–80 Pg of CO_2 on the global scale annually (Raich and Potter, 1995; Raich et al., 2002) and makes up 20–40% of the total annual input of CO_2 into the atmosphere (Raich and Schlesinger, 1992; Schimel, 1995). It has been hypothesized that relatively small climatically induced changes in soil CO_2 efflux could rival the annual fossil fuel loading of atmospheric CO_2 (Jenkinson et al., 1992; Raich and Schlesinger, 1992). Nonetheless, our understanding of soil processes is very limited, constraining our confidence in estimating projected changes in the global C budget (e.g., Davidson et al., 2000; Giardina and Ryan, 2000).

While 30% of global land area is covered with forest (FAO, 2007), soil CO_2 efflux rates in different forest types are poorly understood (Raich and Tufekcioglu, 2000; Hibbard et al., 2005). While some studies have shown that deciduous forest sites have higher soil CO_2

* Corresponding author. Tel.: +82 2 880 5650; fax: +82 2 873 5109.
E-mail address: leedw@snu.ac.kr (D. Lee).

0038-0717/$ – see front matter © 2009 Elsevier Ltd. All rights reserved.
doi:10.1016/j.soilbio.2009.12.005

efflux rates than coniferous forest sites (e.g., Raich and Tufekcioglu, 2000; Wang et al., 2006), other studies have shown that soil CO_2 efflux in coniferous forest sites is significantly higher than that in deciduous forest sites (Brüggemann et al., 2005; Paré et al., 2006). Interestingly, data assembled from 31 AmeriFlux and CarboEurope sites show that soil CO_2 efflux is significantly higher in mixed forest sites than in deciduous forest and coniferous forest sites (Hibbard et al., 2005). Several factors may cause the observed differences in soil CO_2 efflux in different forest types. Those include different litter quality and production rates (e.g., Wardle, 1992); different biomass and quality of root systems (e.g., Lee and Jose, 2003); differences in nutrient cycling rates in detritus (Vogt et al., 1986) and soils (e.g., Paré et al., 2006); and plant-mediated effects on soil microclimate, such as soil temperature and soil moisture (e.g., Raich and Schlesinger, 1992; Aussenac, 2000), and plant-mediated effects on root and rhizomorph dynamics (Vargas and Allen, 2008b). In contrast to these findings, some studies have reported no significant differences among forest types, suggesting that soil CO_2 efflux rates are not significantly influenced by vegetation (e.g., Borken et al., 2002). As a matter of fact, the biophysical mechanisms that regulate soil CO_2 fluxes remain unclear, and there is a need for additional studies to better understand soil CO_2 efflux and control factors under different forest types.

One critical factor that has been considered important in the regulation of soil CO_2 efflux is the effect of soil rewetting following a rainfall event. Birch (1958) and others (e.g., Van Gestel et al., 1991; Pumpanen et al., 2003) have reported that soil CO_2 efflux increases rapidly when dried soils are remoistened. Such an increase in soil CO_2 efflux has been observed in agricultural soils (e.g., Mikha et al., 2005), forest soils (e.g., Vargas and Allen, 2008a), grassland soils (e.g., Xiang et al., 2008), peatland soils (e.g., Knorr et al., 2008), and desert soils (e.g., Sponseller and Fisher, 2008). Observed increases of soil CO_2 efflux rates range from 50% to more than 1000% after a rewetting event (e.g., Fierer and Schimel, 2003; Saetre and Stark, 2005), and these CO_2 pulses substantially influence the carbon (C) balance of terrestrial ecosystems (Lee et al., 2004; Xu et al., 2004). The increase may be attributed to several factors. First, a large proportion of the soil microorganisms die during the period of drought, and their dead cells decompose during rewetting (e.g., Van Gestel et al., 1991). Second, microorganisms accumulate high concentration of solutes (osmolytes) in order to retain water inside the cell during the period of drought (Harris, 1981). The microorganisms dispose of the osmolytes rapidly upon rewetting, either by respiring, polymerizing, or transporting them across the cell membrane, and the osmolytes decompose during rewetting (e.g., Schimel et al., 2007). Third, organic matter accumulates in the soil during the period of drought. Upon rewetting, the microbial population recovers and starts utilizing the fresh dead organic matter in the soil (e.g., Pumpanen et al., 2003). Fourth, additional water also activates CO_2 efflux in living roots through an increase in root growth (Liu et al., 2002) and mycorrhizal metabolic activity (Heinemeyer et al., 2007; Vargas and Allen, 2008b). Fifth, rewetting of dry soil may cause the disruption of soil aggregates, exposing physically protected organic matter, and thus increase the accessibility of substrate that can be rapidly mineralized (e.g., Miller et al., 2005). Sixth, rainfall releases the CO_2 bound to soil carbonates (Emmerich, 2003), and the infiltration of rainwater may displace CO_2 that accumulates in soil pore space during dry periods (Huxman et al., 2004). While there are numerous reports of changes in soil CO_2 efflux after rewetting, few studies have considered the effect of rewetting and possible control factors on soil CO_2 efflux in different forest types.

The main objective of this study was to determine the control factors responsible for temporal variation in soil CO_2 efflux and the effect of rewetting on soil CO_2 efflux in deciduous, coniferous, and mixed forests in the central part of the Korean Peninsula. We measured soil CO_2 efflux and environmental factors in adjacent patches of deciduous, coniferous, and mixed forests over the course of one year, during which we were able to observe the effects of rewetting events. Additionally, we conducted laboratory rewetting incubation experiments with soils taken from each site in order to test whether soil conditions influence the response of soil CO_2 efflux to rewetting under controlled conditions. We hypothesized that (1) soil temperature is a primary control factor in regulating soil CO_2 efflux, but soil moisture modulates the effect of rewetting on soil CO_2 efflux in forested sites; and (2) observed rates of soil CO_2 efflux and the effect of rewetting on soil CO_2 efflux would differ among forest types because soil microclimate (e.g., Raich and Schlesinger, 1992; Aussenac, 2000), soil nutrient dynamics (Borken and Beese, 2005; Paré et al., 2006), and root and rhizomorph dynamics (Vargas and Allen, 2008b) vary among forest types.

2. Materials and methods

2.1. Site description

We conducted our study at three sites in deciduous, coniferous, and mixed forests, all located in the Gwangneung Experimental Forest (GEF) watershed, Kyung-Gi Province, South Korea, from April 2002 to April 2003. Within the GEF watershed, each vegetation type is associated with a different terrain slope. The three sites were different from one another in terms of overstory species, vegetation area, canopy height, and topological features including slope and aspect, but similar in terms of soil type and elevation (as summarized in Table 1). The vegetation of the coniferous forest and mixed forest sites was planted and managed, whereas the deciduous forest site was a preserved natural deciduous forest with no recent human disturbance. In order to measure soil CO_2 efflux and abiotic and biotic factors, we installed five 1 m × 1 m plots along the terrain contour of each site, where distance between the plots were 5 m. Our plot-based sampling scheme provided five replicates for each site on each field survey date owing to five plots at each site.

2.2. Measurement of soil CO_2 efflux and biophysical variables

For each plot, we measured soil CO_2 efflux and relevant soil environmental variables biweekly or monthly. Measured variables included soil temperature (ST), soil moisture (SM), soil organic matter content (SOM), soil total organic carbon (TOC) and total nitrogen (TN). Soil CO_2 efflux was measured by a gas-collecting closed-path chamber (10 cm diameter × 15 cm height; SRC-1, PP system, Hitchin, UK) with an infrared gas analyzer (EGM-4, PP system, Hitchin, UK) for 120 s and the measurements were carried

Table 1
Description of experimental sites.

	Deciduous forest site (DBF)	Coniferous forest site (ENF)	Mixed forest site (MF)
Location	N 37°44′ E 127°09′	N 37°45′ E 127°09′	N 37°45′ E 127°09′
Dominant plant species	*Quercus acutissima, Acer palmatum, Fraxinus rhynchophylla*	*Pinus koraiensis*	*Acer palmatum, Quercus acutissima, Pinus koraiensis*
Soil type	Sandy loam	Sandy loam	Sandy loam
Vegetation age (years)	80–200	70–80	70–80
Canopy height (m)	18–20	16–18	16–18
Elevation (m.s.l)	330	340	320
Surface slope (%)	20	50	57
Aspect	East	North	East

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