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Continuous measurement of CO_2 flux through the snowpack in a dwarf bamboo ecosystem on Rishiri Island, Hokkaido, Japan

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Abstract

To investigate the dynamics and environmental drivers of CO_2 flux through the winter snowpack in a dwarf bamboo ecosystem (Hokkaido, northeast Japan), we constructed an automated sampling system to measured CO_2 concentrations at five different levels in the snowpack, from the base to the upper snow surface. Using a gas diffusion approach, we estimated an average apparent soil CO_2 flux of 0.26 μmol m^{-2} s^{-1} during the snow season (December−April); temporally, the CO_2 flux increased until mid-snow season, but showed no clear trend thereafter; late-season snow-melting events resulted in rapid decreases in apparent CO_2 flux values. Air temperature and subnivean CO_2 flux exhibited a positive linear relationship. After eliminating the effects of wind pumping, we estimated the actual soil CO_2 flux (0.41 μmol m^{-2} s^{-1}) to be 54% larger than the apparent flux. This study provides new constraints on snow-season carbon emissions in a dwarf bamboo ecosystem in northeast Asia.

Keywords: Carbon cycle; Snowpack; CO_2 flux; Concentration-gradient approach; Wind pumping

1. Introduction

It has been suggested that the rate of global warming during the spring is greater than that in other seasons, thereby shortening the duration of snow cover in mid-latitude regions of the Northern Hemisphere (Brown, 2000). This phenomenon could, in turn, affect processes related to biogeochemical carbon and nitrogen cycling in terrestrial ecosystems (Brooks et al., 2011; Kim et al., 2007; Williams et al., 1998). Although snow-season air temperatures range from −20 to >0 °C, subnivean soil temperatures can exceed 0 °C as a result of snowpack insulation (Brooks et al., 1997). The combination of warm soil temperature and meltwater promotes high heterotrophic microbial activity and elevated CO_2 production through the mineralization of soil organic matter (SOM) (Brooks and Williams, 1999; Lipson et al., 2009; Schadt et al., 2003; Zinger et al., 2009). Consequently, CO_2 flux through the snowpack at mid to high latitudes and altitudes is an important contribution to the annual carbon budget (Björkman et al., 2010; Grogan, 2012; Welker et al., 2000). However, difficulties in accessing and working in these snowfield environments have limited the study of this topic, resulting in fewer

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reports quantifying carbon emissions during the winter than during the growing season (e.g., Fang et al., 1999; Morgner et al., 2010; Euskirchen et al., 2006).

Several approaches have been developed to estimate CO_2 fluxes from the snowpack, including those based on concentration gradients, closed chamber measurements, and eddy covariance methods (Bjorkman et al., 2010). Of these, the concentration gradient approach, pioneered by Sommerfeld et al. (1993), is the most widely used (McDowell et al., 2000; Schindlbacher et al., 2007). The method has three proven advantages over other techniques: (1) it allows for continuous sampling and long-term deployment of instruments; (2) it is applicable to different ecosystem structures, snowpacks, and terrains; and (3) it does not disturb the natural soil microenvironment beneath the snow. However, this approach can be affected by wind-related pressure pumping, leading to systematic underestimations of the CO_2 flux on timescales of several minutes to several hours (McDowell et al., 2000; Suzuki et al., 2006). Multiple studies have confirmed the presence of the wind-pumping effect, and a few have estimated the corresponding decrease in the CO_2 flux (Bowling and Massman, 2011; Suzuki et al., 2006). Recently, Seok et al. (2009) evaluated the concentration gradient approach using a multi-layer sampling system, and found that wind-related pressure pumping during midwinter decreased both snowpack CO_2 concentrations and flux by as much as 57%.

Numerous studies have employed the concentration gradient approach to explore CO_2 fluxes from the snowpack in a variety of ecosystems. However, temporal variability, magnitudes of the flux, and controlling factors differ widely among studies. For example, whereas some studies have documented minimal CO_2 fluxes during midwinter, for example in boreal forests (Hardy et al., 1995; Jones et al., 1999; Schindlbacher et al., 2007; Zimov et al., 1996), others have found that CO_2 fluxes in boreal forests and the Arctic tundra remain steady throughout the snow season (Mariko et al., 2000; Sullivan et al., 2008). In Rocky Mountain meadows, wetlands, and coniferous forests, CO_2 fluxes increase during snowmelt events (Liptzin et al., 2009; Mast et al., 1998; Sommerfeld et al., 1993, 1996). Studies in mid-latitude regions (40°N–60°N) have demonstrated that average carbon emissions during the snow season range from less than 100 g C m^{-2} in Japanese cool temperate forests (Mariko et al., 2000) to 189 g C m^{-2} in the Rocky Mountains (Liptzin et al., 2009). The primary environmental factors controlling subnivian soil CO_2 flux were found to be snow depth (Sommerfeld et al., 1996), soil temperature (Brooks et al., 1998; Monson et al., 2006a,b; Sullivan, 2010), soil moisture (Liptzin et al., 2009; Mast et al., 1998), and air temperature (Kim and Kodama, 2012; Takagi et al., 2005).

Dwarf bamboo (*Sasa app.*, Poaceae) is an evergreen understory species found in the temperate forests of northeast Asia (Numata, 1970; Umeki and Kikuzawa, 1999). In Hokkaido, Japan, dwarf bamboo occupies 90% of the forest floor and 60% of the total prefecture area, and accounts for 30% of wood biomass (Seki, 2011). In a typical Hokkaido forest dominated by Mongolian oak, dwarf bamboo accounts for 71% of the total fine-root biomass (Fukuzawa et al., 2007). This understory and below-ground dominance of dwarf bamboo inhibits natural forest regeneration (Noguchi and Yoshida, 2004). Furthermore, as a consequence of the earlier onset snowmelt and decreased soil moisture resulting from global warming, dwarf bamboo has expanded its range in alpine snow meadows by 26% over the last 32 years, and increased its annual growth rate by 30%–150% in culms density and 39 cm in rhizomes (Kudo et al., 2011). Takagi et al. (2009) reported that dwarf bamboo fixes carbon rapidly, restoring forest gross primary production (GPP) to pre-harvest levels within a few years of clear cutting, and contributes significantly to ecosystem respiration (Re) via root respiration. However, little is known regarding the carbon balance of dwarf bamboo-dominated ecosystems during winter.

We examined soil CO_2 fluxes beneath winter snowpack in a dwarf bamboo-dominated ecosystem in Hokkaido, Japan. Our goals were (1) to identify the magnitude and temporal variability of CO_2 fluxes under the snowpack in these ecosystems and (2) to investigate the environmental factors influencing these patterns.

2. Methods

2.1. Site description

We conducted our study on Rishiri Island (~182 km^2), an area of protected natural habitat located within the Rishiri-Rebun-Sarobetsu National Park. Mt. Rishiri (1721 m), a Quaternary stratovolcano, lies at the center of the island. Species found on the mountain's western and southeastern flanks and on the summit include Glehn's spruce (*Picea glehnii*), Jezo spruce (*Picea jezoensis*), Todo fir (*Abies sachalinensis*), Erman's birch (*Betula ermanii*), black alder (*Alnus maximowiczii*), and dwarf Siberian pine (*Pinus pumila*) (Haruki et al., 2004). The Rishiri Observatory (RIO) experiment site is located at the foot of Mt. Rishiri,