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Controls over pathways of carbon efflux from soils along climate and black spruce productivity gradients in interior Alaska

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Abstract

Small changes in C cycling in boreal forests can change the sign of their C balance, so it is important to gain an understanding of the factors controlling small exports like water-soluble organic carbon (WSOC) fluxes from the soils in these systems. To examine this, we estimated WSOC fluxes based on measured concentrations along four replicate gradients in upland black spruce (*Picea mariana* [Mill.] BSP) productivity and soil temperature in interior Alaska and compared them to concurrent rates of soil CO_2 efflux. Concentrations of WSOC in organic and mineral horizons ranged from 4.9 to 22.7 g C m^{-2} and from 1.4 to 8.4 g C m^{-2}, respectively. Annual WSOC fluxes (4.5–12.0 g C m^{-2} y^{-1}) increased with annual soil CO_2 effluxes (365–739 g C m^{-2} y^{-1}) across all sites ($R^2=0.55$, $p=0.02$), with higher fluxes occurring in warmer, more productive stands. Although annual WSOC flux was relatively small compared to total soil CO_2 efflux across all sites ($<3\%$), its relative contribution was highest in warmer, more productive stands which harbored less soil organic carbon. The proportions of relatively bioavailable organic fractions (hydrophilic organic matter and low molecular weight acids) were highest in WSOC in colder, low-productivity stands whereas the more degraded products of microbial activity (fulvic acids) were highest in warmer, more productive stands. These data suggest that WSOC mineralization may be a mechanism for increased soil C loss if the climate warms and therefore should be accounted for in order to accurately determine the sensitivity of boreal soil organic C balance to climate change.

Keywords: Dissolved organic carbon; Soil respiration; Carbon balance; Water balance; Climate change; *Picea mariana*; High latitude; Boreal forest; Fire

1. Introduction

It is widely accepted that positive feedbacks exist between the increasing atmospheric concentration of CO_2 and global warming (e.g. Chapin et al., 2000), and therefore the ability of soils to accumulate and preserve mineralizeable organic matter has received growing interest. The likely direction of change in soil organic carbon (SOC) in the boreal forest biome, which harbors the world's second largest SOC stock, is of marked concern because climate warming is projected to be greatest in high latitudes (e.g. Arctic Climate Impact Assessment team, 2004) and temperature is the cardinal determinant of soil C mineralization. In boreal forests, SOC balance is often the small residual of two much larger C fluxes (inputs from net primary production and losses via soil heterotrophic respiration), and therefore small changes in these two fluxes can change the sign of C balance in these systems (Goulden et al., 1998), and thereby alter the sensitivity of boreal forest C balance to climate change.

Perhaps the least studied component of ecosystem C cycling in boreal forests is water-soluble organic C (WSOC) movement with the mass flow of water from upland soils. Across a boreal landscape in northern Canada (BOREAS study), Moore (2003) showed that WSOC measured in situ from upland organic soil horizons ranged from 2.0 to 6.3 g WSOC m^{-2} throughout the growing season. Although these fluxes were small relative to SOC stocks measured to 5 cm in the mineral soil in upland black spruce forests from the same study (0.01–0.10%; Trumbore and Harden, 1997), accounting for this flux could offset 4.3–45.3% of mean area-weighted SOC accumulation per year across the region (13.9–46.4 g C m^{-2} y^{-1}; Rapalee et al., 1998). Moreover, black spruce stands in the same study region have been shown to vary widely in their net C uptake (10 ± 50 g C m^{-2} y^{-1}; Goulden et al., 1998) and therefore even small soil WSOC fluxes could negate the C sink status of

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these systems. A better understanding of the mechanisms behind soil WSOC flux is necessary in ascertaining the sensitivity of boreal forest C balance to changing regimes of climate and primary production.

Water throughput in forest soils is largely controlled by the sorptive capacity of soil organic matter (SOM), topography, and evapotranspiration (e.g. Fisher and Binkley, 2000). In black spruce forests of interior Alaska, aspect and landscape position play pivotal roles in mediating insolation, soil temperature, and stand productivity (e.g. Viereck et al., 1983). In turn, organic horizon depths diminish with increased nutrient mineralization occurring in warmer, more productive stands (Van Cleve et al., 1981, 1983a). This is important to consider because partially decomposed organic soils can contain >80% water by volume and therefore the depths of organic horizons exert considerable control over surface soil hydrology (Boelter and Verry, 1977; Van Cleve et al., 1983b; Van Cleve et al., 1993; D'Amore and Lynn, 2002). Moreover, peak soil water flows are often restricted to organic horizons because mineral soils are usually still frozen during spring snowmelt, especially when permafrost is present (Kane et al., 1992; MacLean et al., 1999). However, biophysical controls over the interaction between soil water flux and WSOC concentration in boreal forests have received little study.

Decomposition environment and leachates from plant-derived inputs may exert considerable control over the concentration of WSOC in boreal forests. In temperate systems, WSOC concentrations increase with litter fall inputs to and turnover within surface organic soil horizons (Huang and Schoenau, 1996; Park et al., 2002) because of subsequent leaching of the products of microbial decay (McDowell and Likens, 1988). Soil WSOC concentrations increase with microbial activity (Williams and Edwards, 1993), fungal abundance (Guggenberger et al., 1994; Högberg and Högberg, 2002), temperature (Christ and David, 1996), and with almost any conditions that enhance SOC mineralization (Kalbitz et al., 2000; Michalzik et al., 2001). Neff and Hooper (2002) have also shown a positive correlation between CO_2 and WSOC fluxes in laboratory incubations of Alaskan soils, which suggests that WSOC concentrations may increase as microbial processing within soils increases. Field measurements of these fluxes and their environmental controls in boreal forests are rare and poorly understood, however.

Soil respiration increases with temperature and turnover of plant-derived inputs in boreal forests (Schlentner and Van Cleve, 1985; Rustad et al., 2001; Vogel et al., 2005). Mineralization of soil WSOC also contributes greatly to total soil respiration (Qualls and Haines, 1992; Neff and Asner, 2001; Kalbitz et al., 2005), but the degree of WSOC mineralization in high latitudes is highly dependent on its composition (Michaelson et al., 1998). Ping et al. (2001) found that microbial CO_2 production (and hence, activity) increased with the proportion of relatively labile soil WSOC fractions in Alaskan tundra soils. Hydrophilic neutral (HiN) fractions of WSOC generated the most CO_2 in incubation experiments, and were therefore the most labile (Michaelson et al., 1998). The bioactivity of other fractions decreased in the order: hydrophobic neutrals (HoN), low molecular weight fulvic acids (LMWFA), humic acids (HA), and fulvic acids (FA). This continuum of WSOC bioactivity may be used to gain insight as to the environmental controls over WSOC fractions in the field. For example, Michaelson and Ping (2003) suggested that the ratios of hydrophilic to hydrophobic WSOC (Hi:Ho; including all neutral and acid fractions) were higher in colder, permafrost dominated sites due to temperature preservation of more labile organic matter. In addition, saturated soils in arctic Alaska, where O_2 diffusivity may limit microbial activity, exhibited higher HA:FA ratios than did better drained soils of the region (Ping et al., 1988, 2001). Quantifying relative changes in soil WSOC forms and concentrations, in addition to soil respiration, along gradients in temperature and productivity should therefore provide insight as to the mechanisms behind WSOC and its influence on soil CO_2 efflux (e.g. Weller et al., 1995; Stottlemyer, 2001).

To determine how the complex interplay among stand production, nutrient mineralization, and soil temperature affects soil WSOC dynamics, we measured WSOC concentrations, composition, and soil CO_2 efflux along four replicate gradients in black spruce stand production and soil temperature in interior Alaska. Because turnover of SOM is faster in warmer, more productive sites, we hypothesized: (1) the products of SOM turnover, and therefore soil WSOC concentrations, increase with soil respiration in warmer, more productive stands, which suggests that (2) the lability of WSOC fractions decreases as soil respiration, temperature, and stand production increase, and that (3) fluxes of WSOC increase with soil respiration, stand production, and temperature because of diminished soil water holding capacity and increased WSOC concentrations.

2. Materials and methods

2.1. Sites and soil profile descriptions

Site establishment, temperature records, and soil profile and stand descriptions and analyses in this study were previously described in detail by Kane et al. (2005). Briefly, four replicate gradients in black spruce (*Picea mariana* (Mill.) BSP) productivity and soil temperature were established across interior Alaska, ranging in latitude from 63 to 65°N (~365 km) and in longitude from 142 to 148°W (~550 km) (Fig. 1). Study areas were named for the roads used to access them and were established (from west to east) off of the Parks Highway (P), Murphy Dome Rd. (M), the Elliott Highway (E), and the Taylor Highway (T). Each study area consisted of three sites differentiated by their relative level of stand production, or Site Index. Site index (SI) is defined as the height of stand dominants attained after 50 years, and sites with low (L, 2.5–4.6 m), medium (M, 4.6–7.5 m), or high (H, 8.1–12.5 m) SI values occur within each study area. Each site in this study is denoted by its location and productivity level (e.g. Parks Highway, low-productivity (PL)). Site Index equations had been developed from 292 trees harvested from 33 sites across interior Alaska (Rosner, 2004), of which four sites have