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Seasonal variability in CO_2 transport through snow in a boreal forest

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Abstract We used a chamber method to measure CO_2 flux at the surface of the snowpack within three ecotypes of a northern boreal forest near Thompson, Manitoba, during the winter and spring of 1993-1994. We also measured temperatures and CO_2 concentrations at depth within the soil. Vertical concentration gradients, which were observed throughout the winter, declined as soil temperatures dropped and quickly increased when soil temperatures rose. The changing gradients may have been caused by changes in both CO_2 production and the diffusive characteristics of the soil and/or snow. We observed CO_2 fluxes at the snow surface at all sites throughout the winter. Fluxes were lowest in mid to late February and highest in April. Channeling by inhomogeneities of the snowpack contributed to a high degree of spatial variability. These inhomogeneities appeared as depth hoar, ice structures, density variations, and the seasonal formation of melt wells and ablation rings. Understanding the role of snowpack variability is essential to ultimately estimating winter CO_2 production in boreal forest soils.

INTRODUCTION

In places where the soil is frozen or snow covered for most of the year, it is important to understand both the variation of CO_2 production within the soil and how it is transported to the atmosphere. Soil respiration tends to decrease with lower soil temperatures. However, when photosynthetic uptake by plants is at a minimum, soils can be an important net source of atmospheric CO_2. At high northern latitudes, concentrations of CO_2 in the atmosphere are significantly higher during the winter than during the growing season.

It is not unusual for the winter contribution to the annual amount of CO_2 evolved from the soil to be 20% or more (Woodwell & Dykeman, 1966; Havas & Mäenpää, 1972; Edwards, 1975; Phillipson *et al.*, 1975; Dörr & Münnich, 1987; Coxson & Parkinson, 1987a,b; Solomon & Cerling, 1987; Sommerfeld *et al.*, 1991; Sommerfeld *et al.*, 1993; Zimov *et al.*, 1993). The processes responsible for this evolution appear to change with temperature. Above threshold temperatures dependent on soil type and moisture (typically around −7°C) (Benoit *et al.*, 1972), most of the CO_2 is believed to

originate from the breakdown of organic matter and root respiration. Studies of litter decomposition in the laboratory, and measurements made *in situ*, have found CO_2 evolution from organic soil horizons continuing when temperatures were below 0°C and as low as −6°C (Benoit *et al.*, 1972; Coxson & Parkinson, 1987a,b; Carreiro & Koske, 1992; Zimov *et al.*, 1993). CO_2 respiration by microbial and fungal communities has been monitored under the snow and has been found to be continuous throughout the winter (Coxson & Parkinson, 1987a; Carreiro & Koske, 1992; Vuorinen & Kurkela, 1993). Active microbial populations are maintained even in permafrost (Gilichinsky *et al.*, 1992). Below the threshold temperatures mentioned above, the evolution of CO_2 has been attributed to the "ice cube" effect, the outgassing of previously produced CO_2 from freezing groundwater (Coyne & Kelley, 1971, 1974; Zimov *et al.*, 1993). As temperatures change, both respiration and outgassing are likely to contribute to the measured winter production of CO_2 from different levels within the soil (Zimov *et al.*, 1993).

Measurements of CO_2 fluxes from the snow (Winston *et al.*, 1992; Sommerfeld *et al.*, 1993; Zimov *et al.*, 1993;) and CO_2 concentrations within the snowpack (Solomon & Cerling, 1987; Sommerfeld *et al.*, 1991) have shown that snowpack properties vary widely throughout the season and can exert considerable influence on the transport of gases. The values reported for the diffusion coefficient of CO_2 in snow span an order of magnitude (0.026 to 0.30 $cm^2 s^{-1}$) and depend on season and locale (Solomon & Cerling, 1987; Zimov *et al.*, 1993). Gas transport through snow is also affected by the formation of channels (Solomon & Cerling, 1987; Winston *et al.*, 1992) and other spatial and temporal variations in the morphology of the snowpack (Coyne & Kelley, 1974; Sturm & Johnson, 1991). Changes in CO_2 fluxes measured through snow may be attributed either to changes in the gas transport properties of the snow or to changes in soil CO_2 production or diffusivity.

The work described in this paper was done as part of the Boreal Ecosystem-Atmosphere Study (BOREAS), a study of interactions between the boreal forest biome and the atmosphere. Our purpose was to measure seasonal variations in CO_2 fluxes emanating from the surface of the snowpack in a boreal forest and to understand the fluxes in terms of the winter soil respiration and the gas transport properties of the snow. We established four sites in three forest ecotypes on sandy and clay soils in the BOREAS study area near Thompson, Manitoba, during the winter of 1993-1994. The predominant species of the ecotypes were old black spruce (OBS, *Picea mariana*), young jackpine (YJP, *Pinus banksiana*), and old jackpine (OJP). In addition to measuring CO_2 fluxes at the snowpack surface, we measured temperatures and CO_2 concentrations within the soil. Measurements were made during the periods 14-20 November 1993; 20 January-27 February 1994; and 20-28 April 1994.

METHODS

CO_2 fluxes

We used a floating closed-flow chamber method to measure the flux at the snowpack surface (Fig. 1). A plexiglass ring supported the chamber and sealed it against the surface of the snow. The air within the chamber was continuously circulated through an infra-red gas analyzer (IRGA) (Model LI-6200, LI-COR Inc., Lincoln, Nebraska; no

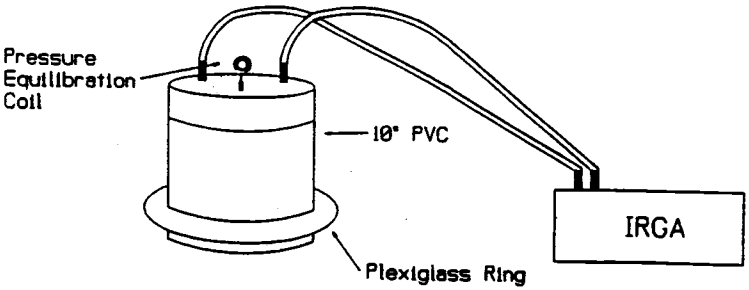

Fig. 1 Chamber and analyzer for measuring CO_2 flux.

endorsement by the U.S. Geological Survey implied) contained within an insulated box which held analyzer temperatures constant during a given run. Testing of the chamber showed that complete mixing occurs within 1 min. We examined the effects of varying flow rates and determined that there was no flow-induced artifact in our flux measurements. We calibrated the IRGA daily with a primary standard mixture of CO_2 in air at ambient air temperatures.

The IRGA recorded CO_2 concentrations every 20 s. For each flux measurement, we recorded ambient air concentrations for 1 to 2 min before placing the chamber on the snow surface. A typical concentration *vs.* time curve is shown in Fig. 2. Fluxes were calculated from the slopes of the concentration vs. time curves and the internal volume of the closed-flow system, and adjusted for temperature and pressure.

The chamber system was modeled to assess the accuracy of our flux measurements (Stephens & Sundquist, unpublished). The modeling results suggest that, for snow depths and diffusivities similar to those encountered in this work, our method measures a flux that is approximately 75-85% of the true local flux, assuming that diffusion is the

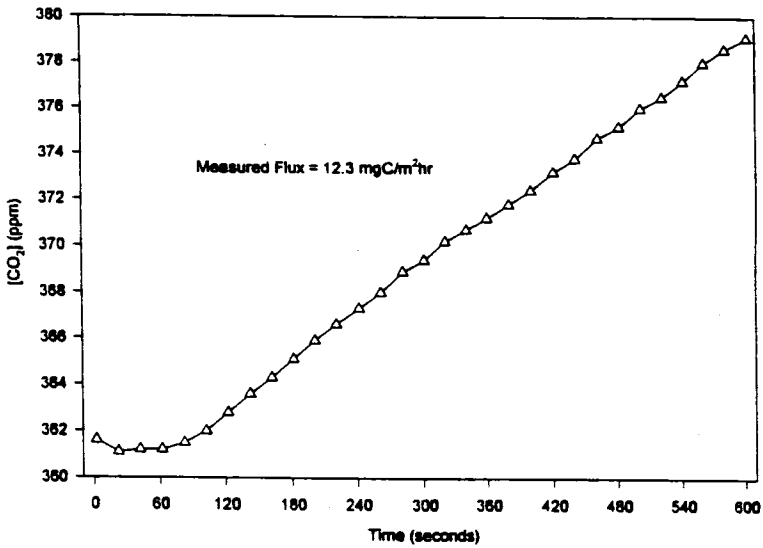

Fig. 2 Typical flux curve for snow chamber method (old black spruce site, 23 January 1994).

only means of gas transport. The closed-flow chamber perturbs the natural CO_2 flux by increasing the concentration of CO_2 at the snow surface relative to the true ambient concentration. This perturbation reduces the diffusion of CO_2 out of the snow, causing a measurement lower than the true flux. According to the model results, this artifact is especially pronounced when measuring flux through a snowpack because of the relatively high porosity of snow. Chamber measurements on soil surfaces would be less affected by this artifact.

We observed that high winds over the snowpack drastically changed our measurements. We believe that under such conditions gas transport through the snowpack is driven by advective processes. These conditions seriously affect the accuracy of chamber measurements such as ours. Measurements reported here were obtained during days when there was little or no wind.

In order to avoid disturbing the snow, we performed our measurements from catwalks supported by wooden frames enclosing 10′ × 10′ areas at each site. By this method the snowpack could be preserved for the entire season and the same sites resampled.

Soil gas CO_2 concentrations

Soil gas probes were made from 1/8-inch stainless steel tubing perforated for 5 cm near the tip. These probes were inserted horizontally at various depths 60 cm into the vertical face of a soil pit. Temperature probes were inserted in the face of the pit at the same depths. Nylon tubing ran from the gas probes to above the snow surface. The probes were installed and the pits backfilled the previous August.

Air temperatures during sampling typically ranged from −20 to −35°C. Syringes are known to be inadequate for the storage of gases at these temperatures (Sommerfeld

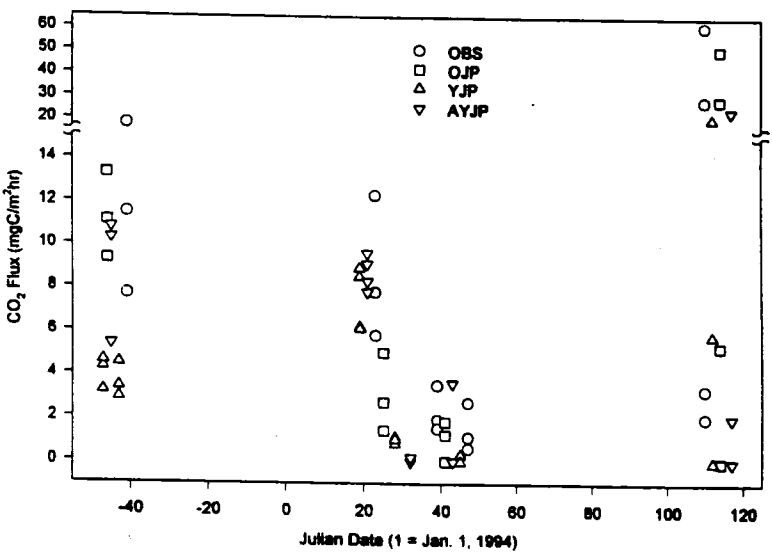

Fig. 3 Seasonal CO_2 flux measurements for the four sites: old black spruce (OBS), old jackpine (OJP), young jackpine (YJP), and auxiliary young jackpine (AYJP).

et al., 1991). To maintain sample integrity, containers were fashioned from coiled 1/8-inch stainless steel tubing closed at each end with a toggle needle valve rated to −55°C. These containers could hold samples for over 24 h at −35°C with no measurable change. We measured CO_2 within 24 h of sampling using an IRGA method similar to a method described elsewhere (Davidson & Trumbore, 1994).

Tortuosity measurements

We collected samples and prepared sections following Perla (1982). We cut, polished and prepared the sections for imaging in the cold room. After digitizing images of the sections we classified them into air and ice phases. We constructed test lines in the air phase, tracing many of the possible streamlines through the pore space. Each tortuosity index is the average of 10 streamline measurements. While tortuosity is a property of the three-dimensional matrix, we believe this method, carried out on a single random section cut vertically through the snow, provides a reasonable index.

RESULTS AND DISCUSSION

CO_2 fluxes varied significantly at each site on each day measurements were made (Fig. 3). The large spatial variability among local fluxes makes it impossible to discern any systematic differences in fluxes from site to site. Several general temporal trends are apparent. CO_2 fluxes declined from November to February, decreasing from a range of approximately 3 to 18 mg C m^{-2} h^{-1} in November to a range of 0 to 4 mg C m^{-2} h^{-1} in February. Soil temperatures were also lowest in mid to late February (Fig. 4). Both soil temperatures and CO_2 fluxes increased between the February and April measurement periods. Fluxes as high as 60 mg C m^{-2} h^{-1} were observed in April through melt wells and low density snow.

A relatively rapid decrease in the fluxes was observed from mid January to early February. This transition appears to have occurred when the deeper soil temperatures dropped below the "threshold" temperature of about −7°C for biological respiration. This observation suggests the possibility of deep sources of CO_2 which remain active until soil temperatures become too cold. Mean air temperatures for February 1994 were 7°C colder than the 29-year average. Consequently, the data presented here may underestimate a typical winter's production.

The hypothesis of deep CO_2 sources is also supported by the soil CO_2 measurements (Fig. 5), which show concentrations increasing with depth at all sites throughout the winter. Temporal trends in soil CO_2 concentrations generally parallel the seasonal changes in fluxes. At the OBS, YJP, and AYJP sites, CO_2 concentrations at depths 40 to 90 cm below the soil surface decreased from a range of about 1100 to 3000 ppm in November to a range of about 400 to 600 ppm in February. Deep CO_2 concentrations at the OJP site were consistently higher, decreasing from about 3000 ppm in November to about 2200 ppm in February. The relatively high deep concentrations measured at this site in February may be associated with an especially persistent deep source of CO_2. However, this source was not reflected in particularly high flux measurements at the OJP site.

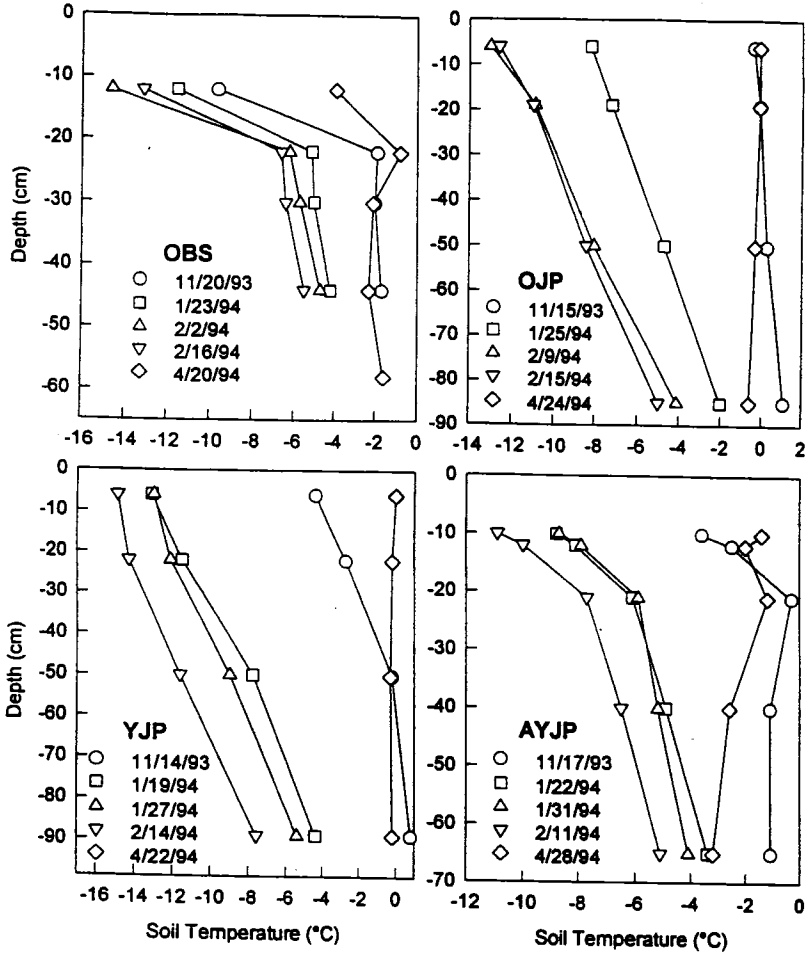

Fig. 4 Soil temperature depth profiles for the four sites: OBS, OJP, YJP, and AYJP.

The higher fluxes observed in April were associated with reversals of the downward-increasing gradients of soil CO_2 concentrations at the OJP, YJP, and AYJP sites. Thus it is likely that the increased fluxes were caused by increased CO_2 production at relatively shallow soil depths.

The seasonal evolution of the snowpack is described elsewhere (Hardy *et al.*, 1995, this volume). The physical properties of the snowpack were relatively homogeneous through February. However, as temperatures began to rise, spatial and temporal inhomogeneities were associated with the development of ice features and melt wells. These inhomogeneities had a strong influence on the spatial distribution of measured CO_2 fluxes, which were more variable in April than during any other measurement period (Fig. 3, Table 1; and Hardy *et al.*, 1995, this volume). The higher fluxes were measured in melt wells and over snowpack which did not appear to have been influenced by frozen meltwater or by snow falling from the canopy. Conversely, lower fluxes were measured over snow containing ice structures or layers.

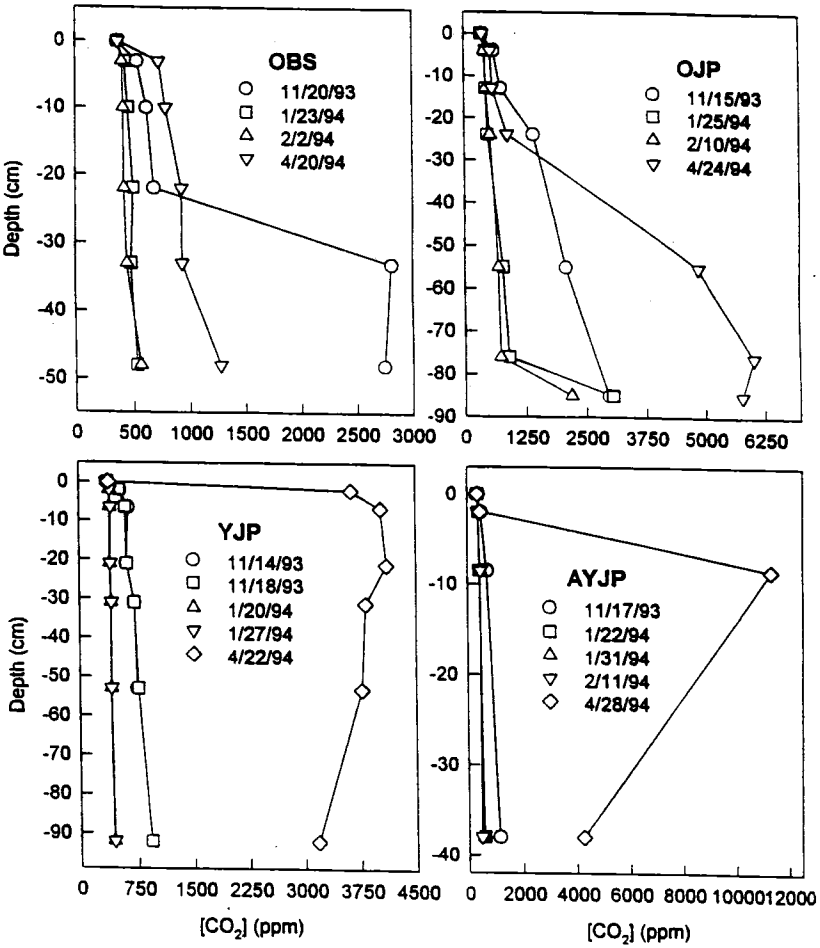

Fig. 5 CO_2 soil concentration depth profiles for the four sites: OBS, OJP, YJP, and AYJP.

We calculated diffusivities of CO_2 through snow using the following equation:

$$D_{eff} = \Theta T D_0$$

where D_{eff} is the effective diffusivity, Θ is the porosity, T is tne tortuosity, and D_0 is the diffusion coefficient of CO_2 in air corrected for non standard temperatures and pressures. Calculated diffusivities, D_{eff}, ranged from 0.081 to 0.099 $cm^2 s^{-1}$ for February conditions. We also estimated diffusivities using Fick's first law, simple one-dimensional steady-state assumptions, snowpack concentration profiles and fluxes measured throughout the winter. The latter calculations yielded a very broad range of diffusivities (0.02-0.5 $cm^2 s^{-1}$), some of which were higher than those previously reported (Solomon & Cerling, 1987; Zimov *et al.*, 1993). The higher values exceed our calculated diffusivities and even the diffusivity of CO_2 in air, suggesting (Zimov *et al.*, 1993) that transport of CO_2 through the snowpack may occur by wind-driven advection

Table 1 Variability in spring 1994 CO_2 fluxes.

Site	Flux (mg C m^{-2} h^{-1})	Snow depth (cm)	Comments (chamber location)
OBS	3.3	20	over glazed snow
	61.2	53	over lens free snow
	2.0	42	over submerged ice lens
	28.5	50	over lens free snow
OJP	5.3	38	over glazed snow
	0.0	24	over glazed snow
	28.8	35	inside alder canopy
	50.9	0	measured inside melt well
AYJP	0.0	33	over glazed snow
	24.1	0	inside melt well
YJP	0.0	34	over glazed snow
	5.8	34	over 6 mm ablation ring
	20.6	0	inside melt well
plot 1- highly developed melt well formation			
	1.1	17	over glazed snow
	12.0	0	center of 7.4 m^2 melt well
	15.1	0	center of 1.1 m^2 melt well
	23.1	0	center of 0.7 m^2 melt well
plot 2- less developed melt well formation			
	4.9	30	over glazed snow
	12.2	0	center of 1.1 m^2 melt well
	15.1	0	center of 0.7 m^2 melt well
	25.5	0	center of 0.4 m^2 melt well

as well as diffusion. Because of our efforts to avoid disturbance of our snow plots, we could not always measure concentration gradients in the snow directly under our chambers and sometimes obtained the samples nearby, possibly contributing errors to these calculations.

Diffusivities of CO_2 through soil were similarly calculated from soil CO_2 concentration gradients, measured fluxes, and one-dimensional steady-state assumptions. The calculated values ranged from 0.002 to 0.3 cm^2 s^{-1}. Again, these values were occasionally much higher than expected. We suggest that the high values may have been obtained when the chamber was placed over channels in the snow through which enhanced vertical transport occurs.

CONCLUSIONS

CO_2 fluxes persisted throughout the winter at all sites observed. Although systematic differences could not be distinguished from site to site, temporal trends in both fluxes and soil CO_2 concentrations suggest a dependence on soil temperatures. Anomalously cold temperatures may have caused fluxes to be lower than normal during the month of

February. Soil CO_2 concentration profiles suggest the persistence of deep sources of CO_2 production throughout the winter, followed by the development of relatively shallow sources in many places by the end of April. The extreme spatial variability of fluxes measured in April was probably caused by inhomogeneous snow properties related to frozen meltwater and proximity to trees. Understanding the seasonal evolution of soil CO_2 sources and snowpack variability is essential to ultimately estimating the contribution of winter CO_2 production to the annual CO_2 budget in boreal forests.

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