Wintertime Net Ecosystem Exchange of CO_2 from the Mer Bleue Bog Peatland: Results from a Field Study

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ABSTRACT

Net ecosystem exchange (NEE) of carbon dioxide from the Mer Bleue bog, an ombrotrophic peat bog near Ottawa, Canada, has been measured year round since 1998 using the eddy-covariance method. Environmental data including, soil temperatures as and meteorological variables have also been measured. An analysis of four winters of data from 1998-1999 to 2001-2002 has been undertaken to evaluate inter-annual variability in wintertime NEE values. During the winter of 2002-2003, field studies to examine the winter CO_2 flux processes were conducted to evaluate the highly variable NEE data collected from the eddy-covariance method. In addition to the ongoing NEE, environmental and meteorological measurements, snow data including pack density and temperature gradients and gas sampling from snow pits were colleted. Concentration profiles of CO_2 in both the peat and snow pack were collected using gas sampling wells. Production of CO_2 was present deep in the peat at a depth of 30cm or more in the hummocks and 20cm or more in hollows. Increasing snow pack depths throughout the winter contributed to increasing snow pack CO_2 concentrations. Wind pumping and convection transport dominated diffusion as the transport mechanism for CO_2 through the snow pack. Eddy-covariance NEE was frequently decoupled from production as a result of different transport mechanisms.

INTRODUCTION

To better understand possible climate change and carbon dioxide concentrations in the atmosphere knowledge of the sources and sinks of carbon dioxide is needed, as well as the response of these sources or sinks to changing climate. A better understanding of the carbon cycle and all possible sources and sinks will allow us to better project climate change and also better estimate carbon dioxide budgets and emissions in conjunction with the 1997 Kyoto Conference Protocol. One of the most poorly understood aspects of the carbon cycle is the terrestrial/atmosphere interface exchange. This interface is important because the terrestrial ecosystems represent a huge pool of carbon, in fact it is estimated that globally the soil contains 1.6 times as much carbon dioxide as the atmosphere (Toland et al., 1994). The large pool of carbon stored in the soil as well as the above ground biomass in these terrestrial ecosystems can represent a large source or sink for carbon dioxide and it is thought that terrestrial ecosystems may be the missing carbon sink in the global carbon budget

In Canada, 14% of the terrestrial landscape is classified as wetlands (Zoltai et al., 1988). Globally the world's northern wetlands represent 25% of the world's soil carbon (Gorham et al., 1991) yet there has only been a limited amount of research involving the flux of carbon dioxide between these terrestrial ecosystems and the atmosphere. There have been few studies conducted on wetlands using the preferred method of eddy-covariance flux measurements (Lafleur et al.,

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2001; Waddington et al., 1998) to obtain a long-term record of CO_2 fluxes between the surface and the atmosphere. However, of the few continuous flux measurement studies that have been conducted, even fewer examine in detail the wintertime fluxes. Many studies give only a single value for the wintertime net ecosystem exchange and offer little explanation for the variation in the efflux values that can total as much as 30% summer flux values (Lafleur et al*.,* 2001; 2003).

The objectives of this field study was to relate changes in the carbon dioxide fluxes and concentration profiles throughout the peat and snowpack to changing meteorological and snow variables and to further our knowledge of the processes of CO_2 production, transport and efflux. This field study was conducted in support of a larger study examining variability in wintertime NEE at the Mer Bleue peatbog over a four year period.

METHODS

The study took place at the Mer Bleue Bog, a northern peatland situated in the Ottawa Valley just 15km Southeast of Ottawa Canada (45^{o}25′N latitude, 75^{o}40′W longitude). The climate for this region is cool-temperate with mean annual temperature of 5.8^{o}C. In the winter, the coldest month is January, with a mean monthly temperature of –10.8^{o}C. Annual precipitation is 910 mm of which 78% is rain. The peatland is a raised ombrotrophic bog that is situated at a mean elevation of 70m above sea level, with an area of 28km^2. The peat depth increases from 2m at the margins to over 5m in the center and it is under laid by a unit of marine clay from the westernmost end of postglacial Champlain Sea. The microtopography consists of raised hummocks covering 70% of the landscape and depressed hollows with an average relief of 0.25m. Vegetation is dominated by mosses, *Sphagnum angustifolium, S. rubellum, S.magallanicum* and scattered sedges (*Eriophorum vaginatum)* both in the raised hummocks and lower lying hollows. Also present on the hummocks are shrubs, *Chamaedaphne calyculata, Ledum groenlandicum, Kalmia angustifolia.* Trees, *Picea mariana and Larix laricina,* occur in scattered patches throughout the bog. Above and below ground vascular plant biomass averaged 356 ± 100 g m^{-2} and 1820 ± 660 g m^{-2}, while moss mass average was 144 ± 30 g m^{-2} (Moore et al. 2002).

All eddy-flux data along with meteorological and environmental data has been collected at the Mer Bleue study site continuously since May 1998 (Lafleur et al., 2001, 2003). Carbon dioxide fluxes were measured using a closed path eddy covariance technique. In addition to the fluxes and their supporting data sets, complete meteorological and environmental data were measured.

Gas sampling to examine the CO_2 production in the soil as well as the movement of CO_2 within the soil and the snow pack, was conducted from December 2002 to March 2003. The soil gas was sampled using 10 manual sampling wells installed at the site (5 in hummocks and 5 in hollows). Samples were taken from depths of: 0cm, -10cm, -20cm and -30cm (Figure 1). The same wells allowed sampling of the air within the snow pack above the soil surface every 10cm to a maximum snow depth of 90cm. The wells were constructed from 2m sections of 19mm PVC tubing that is installed vertically into the peat. Holes were drilled at the depths associated with sampling. The holes below the peat surface have a hollow syringe barrel (*BD 5mL plastic*) sanded flush to the well wall and covered with ©GORTEX, a breathable moisture barrier. The syringe barrel was connected to a length of tubing (ID 0.8mm) that extended the length of the well to the surface where it was connected to one end of double ended syringe needle (©VACUTAINER). Similarly, the samples from above the peat surface were the same except that the syringes were mounted on the out side of the well to extend into the snow pack, away from the well wall. The outer ends of the syringes were covered with ©GORTEX and the inner end was connected to the spaghetti tube that travels into the inside of the well and up to the top where they too end in double ended syringes. Gas samples from the wells were collected in 20ml syringes *(BD disposable Luerlock)* with stopcock fittings.

Additional sampling of snowpack CO_2 was conducted prior to the snow pits being dug. A sampling rod was constructed from doweling that was tapered at the bottom with a single piece of spaghetti tube (I.D. 0.8mm) running the length of the doweling. The tubing ends at the bottom of the doweling where a double ended syringe needle was installed so that the needle would penetrate

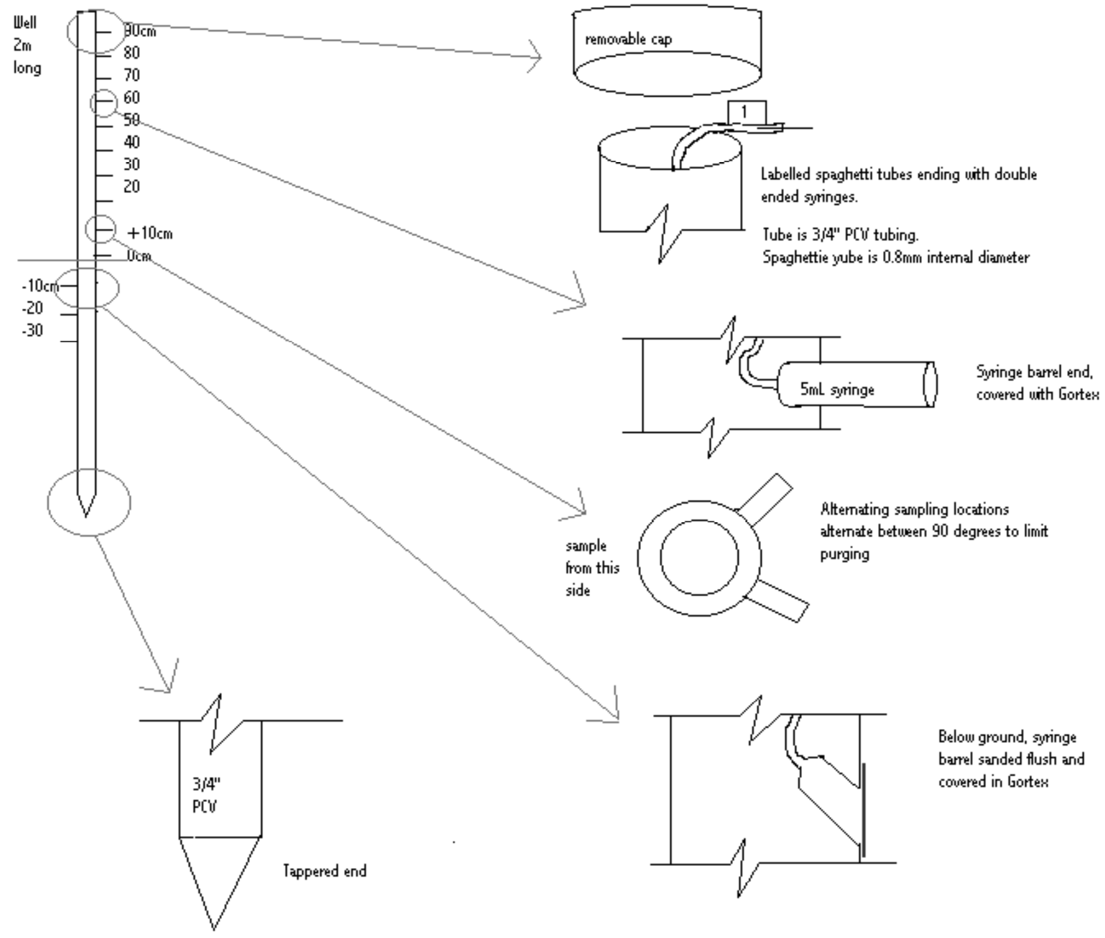

Figure 1: Construction of gas sampling wells used for sampling from the snowpack.

the snow first, followed by the thin tapered doweling. The top end of this tube also was fitted with a double-ended syringe needle to allow sampling using the same syringes and stopcocks as the sampling wells. All collected gas samples both from the sampling wells and the sampling rod were analyzed on-site using a portable IRGA unit (*EGM-2*). The samples were directly injected into the IRGA inlet for static analysis. Excessively wet samples were first passed through a 5mL drying tube filled with an indicating drying agent, which was installed inline with the IRGA inlet. All gas samples were analyzed within 1-4 hours of being collected.

Snow pits were utilized to measure the depth and characteristics (grain size, shape, wetness) of each layer of snow within the pack. Cores were taken from each layer to obtain snow pack density. Integrated cores were also taken to measure the average density of the snow pack at each location. Manual temperatures from within the snow pack coinciding with the snow pack layers were taken from the ten snow pits. Snow depth was recorded manually at 20 hummocks and hollows. Two vertical rods with mounted thermocouples were installed (one hollow and one hummock) and connected to CR21X data logger (Campbell Scientific) to obtain a continuous measurement of the temperature gradient within the snow pack. Data was collected weekly from December 2002 to March 2003.

RESULTS

Snow Environment

Throughout the winter the hollows consistently had a deeper overlying snow pack than the hummocks although the relief between the two decreased throughout the winter. The relief without the presence of snow is estimated at 25cm and was reduced to 12.2cm at the time of peak snow depth. At the commencement of snow melt, snow began to melt earlier over the hummocks decreasing the relief to only 6.6cm. The recorded snow depths had a high degree of spatial variability at the ten hummocks and ten hollow sites, with weekly standard deviations as high as 10cm.

The half hourly snow pack temperature data was validated against manual temperature readings from the snow pits. Diurnal variation and variation from changing meteorological conditions was greatest at the snow surface and decreased with depth towards the soil/snow interface. For the majority of the winter, the possibility of thermally-driven convection existed, with the temperature warmer near the snow/soil interface than at the top of the snow pack. Exceptions included warm days when the surface warms in the afternoon and extended times during periods of melting. The temperature gradients that were favorable for convective transport were more pronounced in the hollows.

In general, snow density increased with depth with the exception of times when a wind crust was present or ice layers formed during periods of freezing rain. The hollows had denser overlying snow packs for the majority of the winter, most likely resulting from the greater mass of the deeper snow pack. Density at the base of the hollows was greater then 0.3 g cm^{-3} for the majority of the winter and was as high as 0.42 g cm^{-3}. The hummocks snow pack density peaked as high as 0.37 g cm^{-3} but rarely reached above 0.3g cm^{-3}.

Soil Environment

Throughout the entire winter study period, the hollow soil surfaces remained at or above the freezing mark with increasing temperature with depth. There was a significant and fairly steady cooling trend in the hollow peat temperatures from December to the end of March. The hummock peat temperatures from 0.2m up to 0.05m follow a similar trend with much more variation through out the winter. The hummock above 0.4m was frozen for the majority of the study period with the exception of several short periods where the temperature peaked near zero. At depths of 0.4m and greater, the hummock remains unfrozen with a similar seasonal cooling trend as the hollow peat temperatures.

Eddy-Covariance Data

The mean daily NEE for the winter was 0.016 mg CO_2 m^{-2} s^{-1}. Throughout the winter there were several days of lower mean daily NEE (0.006 mg $C0_2$ m^{-2} s^{-1}) which, coincide with the presence of a heavy ice layer at the surface resulting from a freezing rain episode. Other mean daily NEE values have lower values due to precipitation events allowing fresh snow to act as a capping layer on fluxes from the snow pack to the atmosphere. Daily NEE values had high variability and ranged from 0.005 mg CO_2 m^{-2} s^{-1} to 0.042 mg CO_2 m^{-2} s^{-1}.

Gas Sampling Wells

Due to the variability in snow depth over both hummocks and hollows, the concentration profiles recorded at each well site was highly variable even between wells of similar micro-topography. There were, however, distinct trends in the data from the hummock and hollow wells. Weekly gas sampling from undisturbed snow pits was used to validate data collected using the wells and to infill missing data points.

Gas sampling from the wells was conducted at a 24-hour interval over 3 days (February 19-21), to examine variations in the concentration profile over a shorter temporal scale than the weekly sampling. Meteorological conditions remained near constant over the sampling period causing almost no variation in the concentration profile. Although this sampling did not result in variations in CO_2 shorter 24-hour period, the ability to reproduce the same profile on three occasions under similar conditions helped to validate the methodology of the gas sampling wells.

Flushing of ambient CO_2 in the snow pack prior to sampling occurred from windy periods prior to sampling (Figure 2). This resulted in overall lower levels of CO_2 in the snow pack since it is purged. The NEE values from the eddy-covariance data within two hours of well sampling on this day were as low as 0.007 mg CO_2 m^{-2} s^{-1} due to the lack of available CO_2 in the snow pack. Wind pumping was much more moderate prior to sampling on several days throughout the study (Figure 3). No convection was possible at these times compounding the effect of no wind pumping. This produced high levels of ambient CO_2 in the snowpack, a linear gradient and NEE values as high as 0.02 mg CO_2 m^{-2} s^{-1}. Periods of CO_2 storage were interrupted by moderate to high winds during hours prior to sampling on several days throughout the study period (Figure 4). The resulting gradient had layers of slightly higher CO_2 inter-bedded within generally lower levels of CO_2. This pattern was also evident in the hollows due to the possibility of convective flow on these days. The NEE at these times was as low as 0.003 mg CO_2 m^{-2} s^{-1} due to an ice layer at the surface and more moderate at 0.014 mg CO_2 m^{-2} s^{-1} at times without the ice layer.

There was strong increasing trend in CO_2 concentration at the bottom of the snow pack with increasing depth of the overlying snow pack in both the hummocks and hollows (Figure 5). Similarly, the increasing snow depth, resulted in increasing CO_2 concentrations in the peat, possibly because as the overlying snow pack acted as a capping layer on the CO_2. The highest concentrations from the wells were recorded at the deepest points at which data could be obtained, 30cm below the hummock surface and 10 to 20cm below the hollow surface. The magnitude of these concentrations was effected not only by the CO_2 production rate, but also by the overlying snow depth and gas transport mechanisms. The high concentration occurring at depth in the peat suggests that CO_2 is produced in the hummocks and hollows simultaneously or production is dominated in either one. Differences in CO_2 concentrations at these depths were not sufficient to distinguish differences in production rates between the hummocks and hollows.

The power functions of CO_2 concentrations and snow depth from Figure 5 was used to predict the CO_2 concentration at the bottom of the snow pack as a function of the measured mean snow depth in the hummocks and hollows. The deviation of the observed concentration from the predicted concentration against the mean wind velocity over the previous 24 hours is summarized in Figure 6. There appears to be a relationship between the changes in concentration at the base of the snow pack with prior wind velocities, although it is most evident within the hummocks.

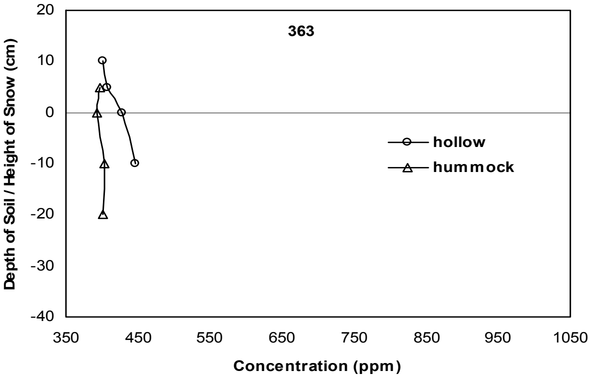

Figure 2: CO_2 profile from gas sampling wells on DOY 363 a time of low wind pumping.

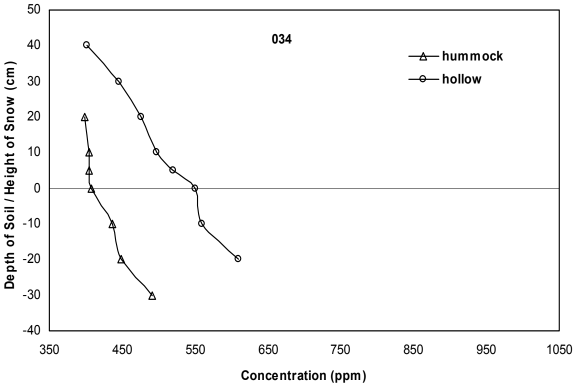

Figure 3: CO_2 profile from gas sampling wells on DOY 034, a time of low wind pumping.

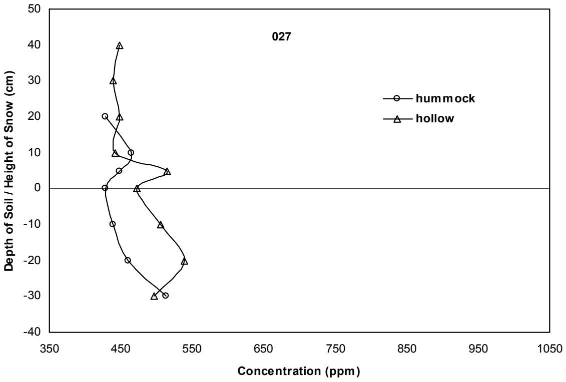

Figure 4: CO_2 profile from gas sampling wells on DOY 027, a time with a prior period of low wind pumping interrupted by a few hours of moderate winds just prior to sampling.

The variations in wind velocity, which can cause times of CO_2 storage and times of wind pumping, can be evaluated using calculated values of vertical air velocities. This value uses not only wind velocities as a variable, but also snow the topographic relief between hummock and hollows and also the snow pack density (Jones et al., 1999). The degree of wind pumping occurring just hours or even minutes before the sampling can alter the CO_2 profile. A wind velocity of 3 m s^{-1} results in a wind pumping vertical velocity of 0.38 m s^{-1}, which could draw air from the base of the pack to the top within 5 minutes. Layers of elevated CO_2 in the upper strata and lowered CO_2 at the bottom of the snow pack, may be a result of wind pumping drawing the CO_2 rich air upwards in pulses in conjunction with periods of higher wind velocity creating a non-steady-state pumping condition (Jones et al., 1999).

The times of CO_2 storage and purging are evident in a time series of half hourly NEE data and vertical air velocity as a result of wind pumping (Figure 7). For example, Julian day 63 to 68 is a time of CO_2 storage under very low wind pumping conditions. As the period of storage continues over an increasing time period, small increases (peaks) in the wind pumping result in large half hour NEE values as the high levels of CO_2 stored in the snow pack are released as fluxes to the atmosphere. At the end of day 67/ beginning of DOY 68, a longer, more intense period of wind pumping occurs. This event quickly purges the pack and very low fluxes are recorded until the end of the wind pumping on day 71. Afterwards, higher flux values are recorded within less than a day of the decrease in wind pumping.

Although there were times when the concentration profiles in the hummocks and hollows were similar, the concentrations at the base of the snowpack in the lower lying hollows which have deeper and denser snow packs, are not effected in the same magnitude by the wind pumping (Figure 6). The temperature gradients in the hollows were much more favorable to convective flow than for the hummocks and consequently, the concentrations at the top of the snow pack in the hollows increases with increasing temperature gradient as a result of convection flow (Figure 8).

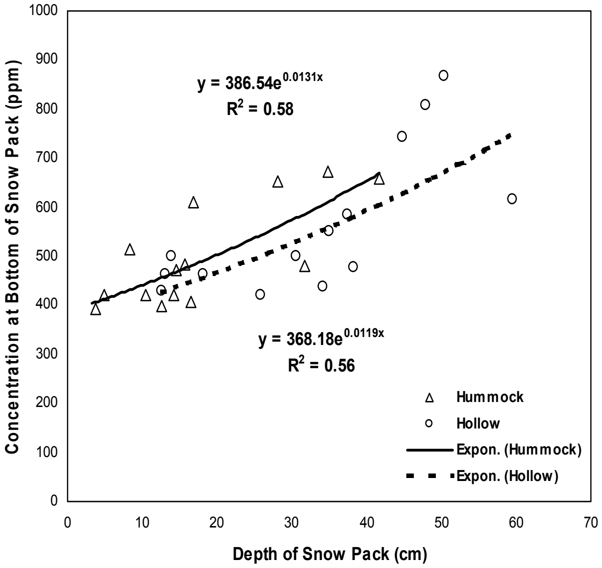

Figure 5: CO_2 at bottom of the snow pack and snow pack depth.

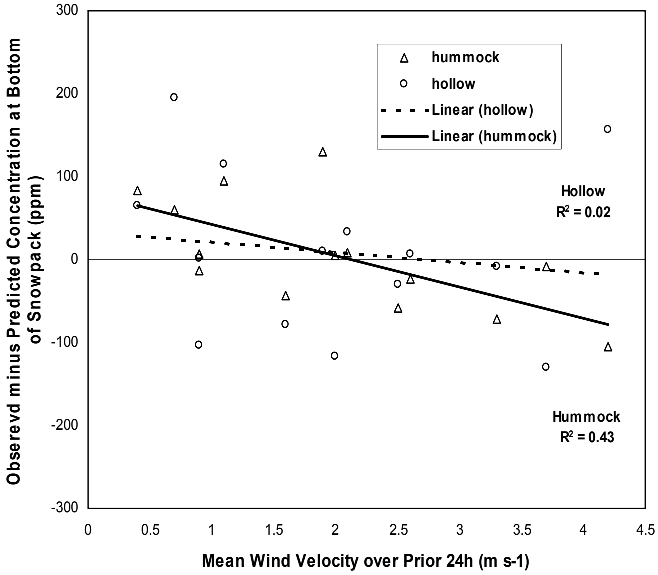

Figure 6: CO_2 at the base of the snowpack and prior wind velocity.

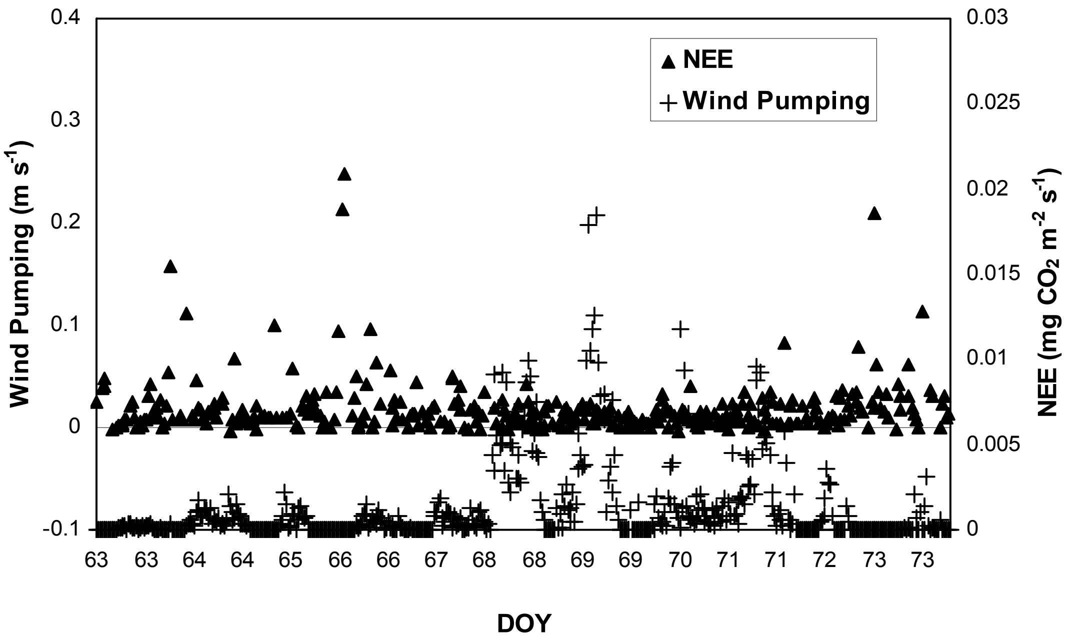

Figure 7: Time series of half hourly NEE and vertical air velocity from wind pumping.

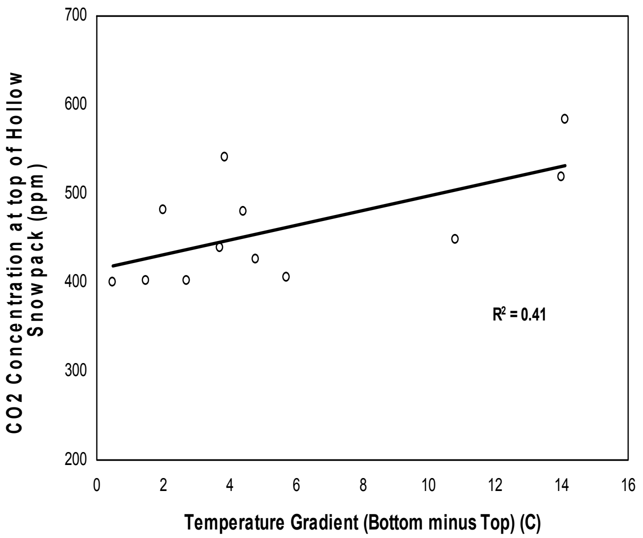

Figure 8: CO_2 concentration at the top of the hollows and snow pack temperature gradients.

CONCLUSIONS

The amount of CO_2 present in the snowpack was largely regulated by the depth of the overlying snow pack, which agrees with other studies (Bubier et al*.,* 2002; Jones et al*.,* 1999). Concentrations in the peat were highest at depth but the magnitude of the concentrations was related also to the snow depth. The amount of wind pumping which was regulated by topographic relief and wind velocity, in addition to convective transport, regulates times of CO_2 storage and purging in the snowpack. This prior history of meteorological conditions directly effects the concentration of CO_2 within the snow pack available to provide a flux to the atmosphere.

In summary, the CO_2 is produced at depth at or greater than 30cm in hummocks and 20cm in hollows. The ambient gas is dispersed through the snow pack by wind pumping over hummocks and thermally driven convection in the hollows during times of flushing and through diffusion during times of CO_2 storage. The eventual flux to the atmosphere is dependent on the surface snow density, current dominant method of CO_2 transport and resulting concentration of CO_2 in the snow pack as a result of prior CO_2 transport history. Variability in NEE data from the eddy-covariance technique can be in part explained through these CO_2 storage or purging episodes, which control the amount of ambient CO_2 in the snow pack available for flux to the atmosphere.

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