P1.20 CONTRASTING THE INTERANNUAL VARIABILITY IN NET ECOSYSTEM EXCHANGE OF CARBON DIOXIDE IN A NORTHERN PEATLAND WITH THE VARIABILITY OBSERVED IN NORTHERN FORESTS

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1. INTRODUCTION

Peatlands of the boreal forest comprise only 17% of the land area, but contain up to 60% of the soil carbon (C) pool. Despite limited plant growth in these often cool and nutrient-poor wetlands, slow decomposition rates have resulted in a small but persistent net uptake of C over thousands of years. However, it has been suggested that climate warming may enhance respiration rates and cause peatlands to become significant annual sources of C. This hypothesis is based largely on observations in other ecosystem types and on laboratory or field experiments in peatlands lasting only a growing season or two. In this study we examine the sensitivity of C exchange processes to seasonal and annual variations in weather using five years of CO_2 flux measurements obtained using the eddy covariance technique at Mer Bleue, a 2800 ha low-shrub bog near Ottawa, Ontario. To emphasize the unique features of C exchange in this bog ecosystem, these results are contrasted with those from published studies of interannual C exchange at boreal forest sites.

2. SITE AND INSTRUMENTATION

The Mer Bleue bog is a large raised, ombrotrophic bog (nutrient and water inputs are received only from rainfall) located east of Ottawa, ON, Canada (45.40°N lat., 75.50°W long.). The 30-year mean air temperature is 6 °C and total precipitation is 943 mm. Using the eddy covariance technique, continuous, ongoing measurements of CO_2 and H_2O flux have been made here since June 1998. A three-dimensional sonic anemometer-thermometer (model R3, Gill Instruments Ltd.), a closed-path infra-red gas analyzer (model LI6252 or LI6262, LI-COR Inc.) and a krypton hygrometer (model KH20, Campbell Scientific Inc.) have been used to measure fluctuations in wind velocity, temperature, CO_2 concentration, and water vapour density 3 m above the bog surface. Net ecosystem exchange of CO_2 (NEE) is computed from the measurements of WPL corrected CO_2 flux and the change in half hour storage of CO_2 between the surface and the height of the eddy covariance instrumentation. The export of dissolved organic carbon and efflux of methane are significant components of the net ecosystem production of this site and are discussed further in Fraser et al. (2001).

Fluxes were removed from the data set during instrument malfunction or when winds came from the direction of the huts and the shoreline (between 130 and 190°). Nighttime CO_2 fluxes where also removed from the data set when friction velocity was less than 0.1 m s^{-1} or when CO_2 fluxes indicated erroneous nighttime C uptake. To complete the data set, gap-filling procedures were used. Missing latent heat fluxes were replaced with an estimate obtained from a relationship with net radiation. This also ensured that the WPL correction was applied to all measured CO_2 flux. Although the absolute NEE computed for the site varied considerably depending on the gap-filling method used to replace missing values, patterns in interannual variations remained consistent between methods (Fig. 1).

In Fig. 1, Method 1 filled missing nighttime values with an annual linear relationship between ln transformed NEE and T_{soil}. In Method 2, estimates obtained with Method 1 were adjusted to match the fluxes measured within a 7 day window period. Method 3 filled missing nighttime values with an annual logarithmic relationship between NEE and T_{soil} with values adjusted as in Method 2. Method 4 filled missing values with the average measured NEE obtained for the 7 day moving window technique. In all methods, missing daytime fluxes were modelled using the combination of an estimate of gross ecosystem production (GEP) from light response curves and daytime ecosystem respiration (ER) from the various nighttime NEE-T_{soil} rela-

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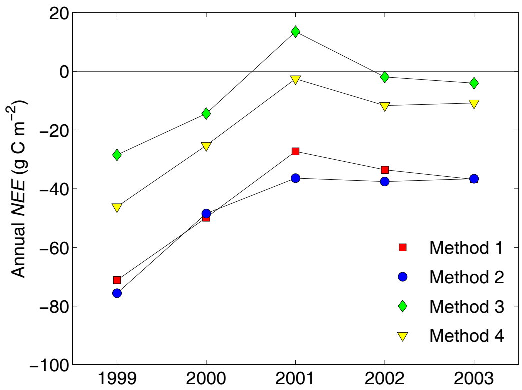

Figure 1: Annual NEE and the influence of various gap filling methods (see text).

tionships. Method 1 was used for the analyses in this paper. Total ER was estimated with daytime T_{soil} and measured or modelled nighttime fluxes. GEP was obtained from $-NEE + ER$. Positive values of NEE and ER indicate a loss of C from the bog. Positive values of GEP indicate a gain of C.

Complementary weather data including the depth of the water table (WTD) and 5 cm soil temperature (T_{soil}) were collected on site. Further details on the site, instrumentation, and calculation procedures are found in Lafleur et al. (2001), Lafleur et al. (2003), and Moore et al. (2002).

3. RESULTS AND DISCUSSION

3.1 Annual Carbon Uptake

During the five-year measurement period at Mer Bleue, the average C uptake was 44 ± 8 g C m^{-2} y^{-1} (± 1 SE) (Fig. 2). Loss of dissolved organic C is about 10 g C m^{-2} y^{-1} resulting in a net ecosystem production of approximately 34 g C m^{-2} y^{-1}, in agreement with the average of 25-30 g m^{-2} y^{-1} estimated for peatlands for the past 6000 years (Gorham 1991). The Mer Bleue NEE values fall approximately in the middle of annual values reported for boreal forests. For example, in southern Saskatchewan, annual NEE in old jack pine and old black spruce stands range from -80 to +20 g C m^{-2} while aspen sequester about 190 g C m^{-2} (Kljun et al. 2004). Annual NEE in old black spruce in northern Manitoba range from +70 to -10 g C m^{-2} (Gower et al. 2004).

Absolute differences in NEE between years at Mer Bleue were less than 40 g C m^{-2} (Fig. 2, Table 1). These conservative responses in absolute NEE to differences in weather are very similar to those observed in boreal black spruce and jack pine stands but are much smaller than those in an aspen stand (interannual differences as large as 260 g C m^{-2}). However, the relative variability in annual C exchange at Mer Bleue is large, for example 2.3 times more net C was sequestered in 1999 than in 2003. This relative interannual variability is only slightly smaller than that observed in boreal forests (Goulden et al. 1998, Kljun et al. 2004). Interannual and seasonal variations in temperature and drought are important in explaining the observed variability in C exchange in these boreal forests. The extent of soil thaw, drought, and spring temperatures affect GEP and/or ER in a variety of ways. At Mer Bleue, the magnitude of the variations in annual GEP was similar to those for annual ER suggesting that increases in ER due to warming do not explain the variability in NEE for this peatland (Fig. 2). The climatic factors which influenced interannual variations in C exchange processes in the bog are explored below.

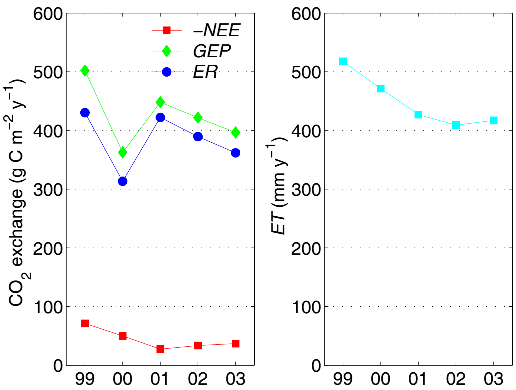

Figure 2: Annual $-NEE$, ER, GEP, and ET.

3.2 Temperature and C exchange

Over the five study years, average air temperature at the site was 6.1 °C. 2003 was the coolest year at 5.1 °C while 1999 and 2001 were the warmest years at 6.8 °C. These values were within ± 1°C of the long-term average air temperatures. The warmest years were not clearly associated with less net C uptake (Table 1, Fig. 2). Warmer years (1999 and 2001) were, however, related to greater ER. This is expected as ER is exponentially related to T_{soil} and a large portion of the ER values estimated with this relationship.

Effects of temperature on C exchange are even more apparent when comparing seasons (Fig. 3). The springs with either the coolest T_{soil} (2003) or the latest snow melt date (2000) (Table 1) had the

Table 1: Selected C exchange and climate characteristics for Mer Bleue.

Year	1999	2000	2001	2002	2003
Annual:					
NEE (g C m^{-2})	-70	-50	-30	-35	-40
ET (mm)	520	470	430	410	420
T (°C)	6.8	5.3	6.8	6.4	5.1
April-May:					
T (°C)	10.7	8.7	10.1	8.6	7.9
T_{soil} (°C)	9.0	7.9	9.4	8.3	7.2
K (W m^{-2})	240	190	220	195	195
June-Sept:					
Max-Min WTD (-cm)	38-69	25-46	33-70	22-74	32-67
January-March/Winter:					
DOY without snow cover	NA	13-34	NA	74-80	88-94
Snow melt DOY	93	123	101	90	100
T_{soil} (°C)	-1.6	-2.1	-1.2	-1.0	-2.7
T (°C)	-6.7	-5.6	-7.3	-4.6	-9.9

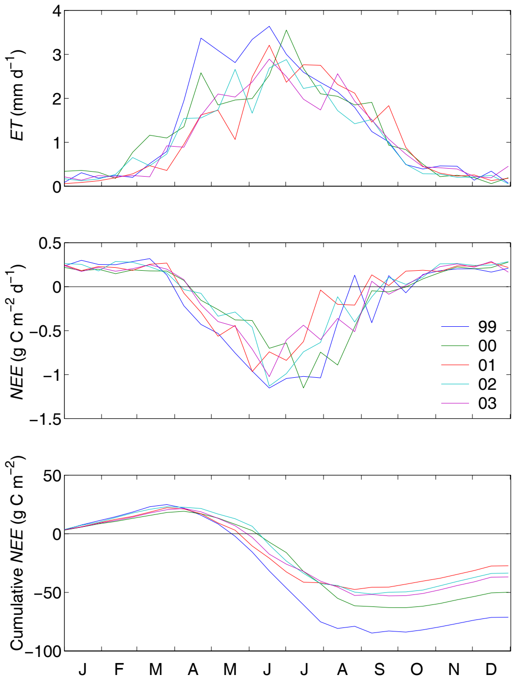

Figure 3: 7-day average ET, NEE and cumulative NEE at Mer Bleue.

most delayed C uptake. The spring with warmest T and early snow melt date had the greatest spring C uptake (1999). These conditions led to more annual C gain in 1999 but the delay in C uptake in 2000 and 2003 did not necessarily result in less annual C gain than in other years. Kljun et al. (2004) found a very predictable trend in spring air temperature, start date of photosynthesis, and annual NEE in boreal aspen but not in boreal jack pine or black spruce. In the latter two forests, cooler springs delayed net C uptake but warm springs did not cause a significant change in the onset of net C uptake. In the aspen, leaf emergence could occur up to a month earlier than in other years and result in an increase in net C uptake from 130 to 360 g C m^{-2} y^{-1}. Since T_{soil} at Mer Bleue is always relatively warm, the onset of leaf emergence and photosynthesis by moss and the various deciduous shrubs can respond rapidly to warming spring air temperatures and light, similar to the aspen stand.

Lafleur et al. (2003) show the importance of snow cover on winter T_{soil} in the bog. Continuous and deep ($>$ 0.1 m) snow cover decouples the soil from the atmosphere and enables the warmth retained within the 5 m of saturated to peat to maintain greater T_{soil} and decomposition rates. Looking at the winter period at the beginning of each year, 2000 was the only year to have a significant early snow-free period resulting in relatively cool T_{soil} despite 1 - 4 ° C warmer air temperatures than most of the other years. Consequently, Jan-March NEE was lowest in 2000 at 16 g C m^{-2} compared with 19-24 g C m^{-2} in the other years.

In the northern Manitoba black spruce forest, interannual variations in ER related better to deep T_{soil} (soil thaw) than to air temperature, particularly during the summer. However, at Mer Bleue, the warmth of deep soil layers (6-8 °C at 2.5 m, year round) ensured that shallower frozen soil layers readily thawed with increasing spring air temperatures. As a result, summer and annual ER related well to summer air temperature and to T_{soil}.

3.3 Hydrological controls on ET, GEP, and ER

Lafleur et al. (2004a) have found that daily ET at this site relate well to potential ET (PET) when WTD is used to classify the data into three groups, high water table ($<$ 25 cm below the surface), moderate water table (65 cm $>$ WTD $>$ 25 cm), and low water table ($>$ 65 cm below the surface). During high, moderate, and low water tables, ET was 62%, 53%, and 43% of PET suggesting increased canopy resistance to evapotranspiration. As the water table descends below the rooting zone of the vascular species and mosses, moss/peat structures conduct less water to the surface and even become completely dessicated while stomatal resistance in vascular species increases. WTD is a result of ET and rainfall and the negative feedback between ET and WTD works to moderate interannual variations in ET during most years.

The most notable anomaly in ET was the high rates in spring 1999 which resulted in the largest annual ET of all the years (Fig. 2 and 3). This was a function of high PET as a result of a warm and unusually sunny spring conditions (Table 1) associated with a moderate water table. The next greatest ET was in the following year when conditions were cool and cloudy but the water table was high all summer due to high rates of spring and summer rain and low PET. The following three years had similar ET. ET was limited in 2001 and 2002 by lower WTD in the late summer while 2003 was cooler with lower PET.

Since low WTD had reduced ET most likely through increased stomatal resistance in vascular plants and dessication of mosses, it was expected that GEP would also show a decline with WTD. Fig. 4 shows that for a given light level GEP was reduced when WTD $<$ -65 cm. GEP was greatest with moderate WTD, possibly since these conditions tend to be associated with warmer conditions for photosynthesis.

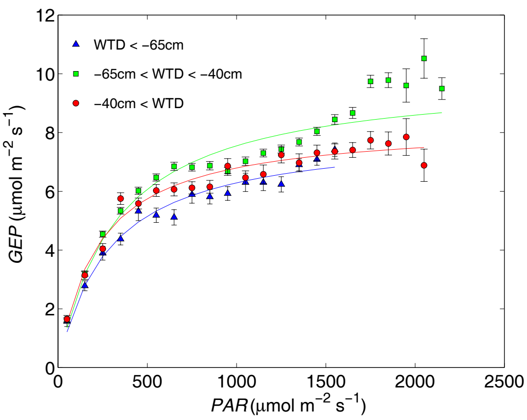

Figure 4: Light response curves for July to August 1999-2003 classified by water table depth.

In contrast to GEP, Lafleur et al. (2004b) found that ER did not depend on WTD. This was likely because Mer Bleue is a relatively dry bog (WTD generally at least 20 cm below the hummock surfaces), there is likely compensation between respiration processes in the upper and lower peat profile, and autotrophic respiration may be relatively independent of WTD.

Responses to drought in the southern Saskatchewan boreal forests varied. Daily GEP in aspen in July and August decreased from 12 to only 6 g C m^{-2} d^{-1} after three years of drought conditions. In contrast, the boreal jack pine and black spruce showed modest reductions in GEP of 2 g C m^{-2} d^{-1} by August of a drought year (GEP approx. 5 and 6 g C m^{-2} d^{-1}, respectively in non-drought years) . These reductions were more similar in magnitude to those at Mer Bleue where daily GEP was on average 4 g C m^{-2} d^{-1} in July 1999 with moderate WTD and between 3 and 3.5 g C m^{-2} d^{-1} in July 2001 with low WTD.

4. SUMMARY AND CONCLUSIONS

Compared to northern boreal forests, differences in annual and seasonal NEE at Mer Bleue between 1999 and 2003 were similar to those in coniferous forests but much smaller than those in an aspen forest. The modest response of GEP to drought (low WTD) at Mer Bleue was similar to that observed in old black spruce and jack pine forests. However, the large thermal inertia of the saturated peat affected the sensitivity and response patterns of C exchange processes to warmer air temperatures when compared with these boreal coniferous forests. Results suggest that in future, warmer winters may decrease C loss from the bog if this also results in greater snow-free periods. Similarly, warmer springs, if accompanied by clear sky conditions, may increase GEP more than ER and thus enhance net C uptake.

The absolute C sink/source strength of the Mer Bleue bog is still in question due to the uncertainties of the eddy covariance technique and gap-filling procedures. However, these results emphasize that by applying consistent data selection and gap-filling methods, interannual variations in NEE and responses to climate remain reliable.

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