12.5 NET CARBON EXCHANGE OF THREE BOREAL FORESTS DURING A DROUGHT

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1. INTRODUCTION

The boreal region forms a nearly continuous circumpolar belt of forest extending between 50° and 70° N in North America, Europe, and Asia. The boreal forest is characterised by subarctic and cold continental climate with long, severe winters and short warm summers, thus a short growing season of often less than 120 days. Interactions between the atmosphere and the vast boreal forest biome, and the impact of climate change on its carbon cycle is of great importance for understanding the global carbon cycle.

The present study analyses eddy correlation flux measurements of CO_2 and climate data obtained at three sites in the Boreal Research and Monitoring Sites (BERMS) program and the Fluxnet Canada Research Network, that were formerly part of the Boreal Ecosystem-Atmosphere Study (BOREAS). The sites, located in northern Saskatchewan near Prince Albert National Park, are in extensive mature stands of aspen (SOA), black spruce (SOBS), and jack pine (SOJP), and less than 100 km apart. The proximity of these sites provides a unique opportunity to compare the responses of different ecosystems to comparable synoptic-scale meteorological forcings and interannual climate variability.

Four recent consecutive years (2000-2003) of measurements from the above sites were analysed. The time series starts with a year with temperature and precipitation well within the long-term average. The subsequent years were affected by a drought occurring in western Canada. In addition, an early (warm) spring occurred in 2001 and 2003, and a late (cold) spring in 2002.

2. SITES AND INSTRUMENTATION

The annual mean air temperature of the three sites is 0.4°C and the annual precipitation 467 mm, most of it is normally received during the summer months in the form of rain (based on the 30-year record 1971-2000 at Waskesiu Lake, Environment Canada, 20 km north of SOA).

Table 1: Site characteristics.

	SOA	SOBS	SOJP
Present age (y)	85	132	82
Stand height (m)	21	7	13
Stand density (stems ha^{-1})	980	6350	1190
LAI (m^2m^{-2})	5.6	4.2	2.4
Height of EC (m a.g.)	39	25	28

The dominant species at SOA is trembling aspen; its understorey is dominated by hazelnut. The overstorey of SOBS is mainly black spruce with only sparse understorey and a thick moss layer. SOJP is of pure structure (jack pine) with lichen, and isolated groups of alder. See Table 1 for more details. The terrain of the three sites is predominantly flat, with gently rolling topography at SOJP, and with a uniform fetch of 1 to 3 km. Footprint calculations using the model of Kljun et al. (2004) showed that the daytime and nighttime footprint of the carbon flux measurements were well within the uniform fetch at all three sites.

The water availability at the three sites depends not only on precipitation but also on soil water retention characteristics. At SOBS, the watertable is usually close to the surface due to poor drainage. At SOJP, on the other hand, water from a rain event quickly drains out of the system (within hours to days). Vegetation at the two conifer sites is thus adapted to high and low water availability, respectively, and only an extremely serious and persistent drought would likely affect these stands. At SOA, the stand with moderate drainage, it is expected that gross ecosystem photosynthesis (GEP) and ecosystem respiration (R) would be clearly affected by changes in precipitation patterns and soil water content.

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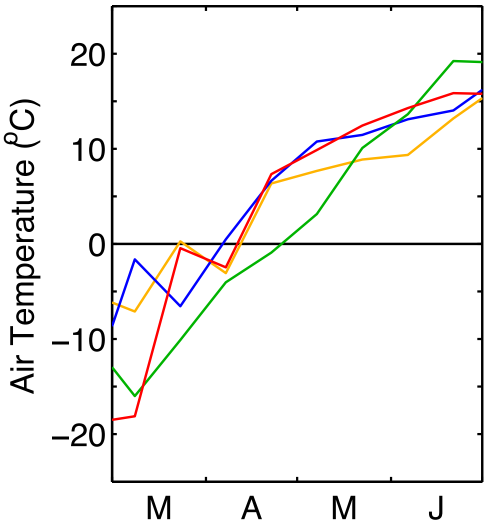

Figure 1: Mean air temperatures (15-day averages) in spring as observed at the three sites in 2000 (orange), 2001 (blue), 2002 (green), and in 2003 (red).

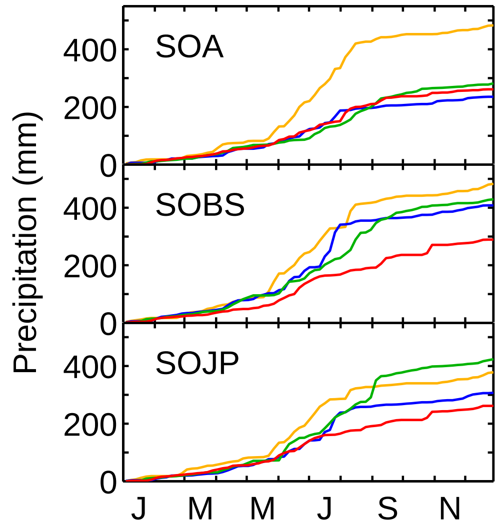

Figure 2: Precipitation observed at the three sites in 2000 (orange), 2001 (blue), 2002 (green), and in 2003 (red).

At all three sites, CO_2 and H_2O fluxes were measured using the eddy correlation (EC) technique. The system included a three-dimensional sonic anemometer-thermometer for measuring wind velocity and temperature fluctuations (R3, Gill Instruments Ltd. at SOA and SOBS, and CSAT3, Campbell Scientific Inc. at SOJP), and a closed-path infrared gas analyser (IRGA 6262, LI-COR Inc.) for measuring CO_2 and H_2O fluctuations. The IRGA was mounted in a temperature-controlled housing on the flux tower. Air was sampled from within 0.3 m of the sonic anemometer, drawn through a heated 4 m long Dekoron tube and pulled through the IRGA at a flow rate of 10 L min^{-1}. More details about the EC systems can be found in Chen et al. (1999) and Blanken et al. (2001). Each site was equipped with instruments for standard climate measurements.

The net ecosystem exchange (NEE) was calculated by adding the EC CO_2 flux measurements, F_C, to the change in storage of CO_2 in the air column. The net ecosystem productivity (NEP) was derived from $NEP = -NEE$. R was obtained from the nighttime relationship between high-u_* NEE and soil temperature. GEP was derived from NEP and daytime R as $GEP = NEP + R$ (Griffis et al. 2003).

3. RESULTS AND DISCUSSION

The climate conditions and the carbon fluxes as observed in 2000 were considered as a reference. Comparing the carbon fluxes at SOA in 2000 with those of previous years (e.g., Black et al. 2000), this assumption is justified.

3.1 Spring Temperatures

The high spring temperatures (mid April-May, Figure 1) of 2001 resulted in an early leaf out (two weeks earlier than in 2000) and early start of carbon uptake (nine days earlier than in 2000) at SOA (Figure 3). Such an early leaf emergence has already been observed during similar spring conditions in 1998 (Black et al., 2000). At the conifer sites, however, photosynthesis started slightly later than in 2000. It was found that the start of photosynthesis at the conifer sites is highly correlated to timing of snow melt and air temperatures in early April rather than mid April and May as for the deciduous forest. Air temperatures in March and early April 2001 were in the same range as the respective values in 2000 (Figure 1).

In 2002, on the other hand, photosynthesis at SOA started two weeks later than in 2000. This is attributed to the cold spring of 2002. The conifer sites, SOBS and SOJP, were also affected by the low temperatures and started photosynthesising three to four weeks later than in 2000.

The spring temperatures in 2003 were again higher than for the reference year. Leaf emergence at SOA in 2003 started as early as in 2001 but the maximum value of LAI was reached ten days layer than in 2001. This points to the fact that the trees were under high water stress and only few clones (aspen usually grows in clones) started photosynthesis as early as in 2001. At the conifer sites, start of photosynthesis was comparable to the timing in 2000.

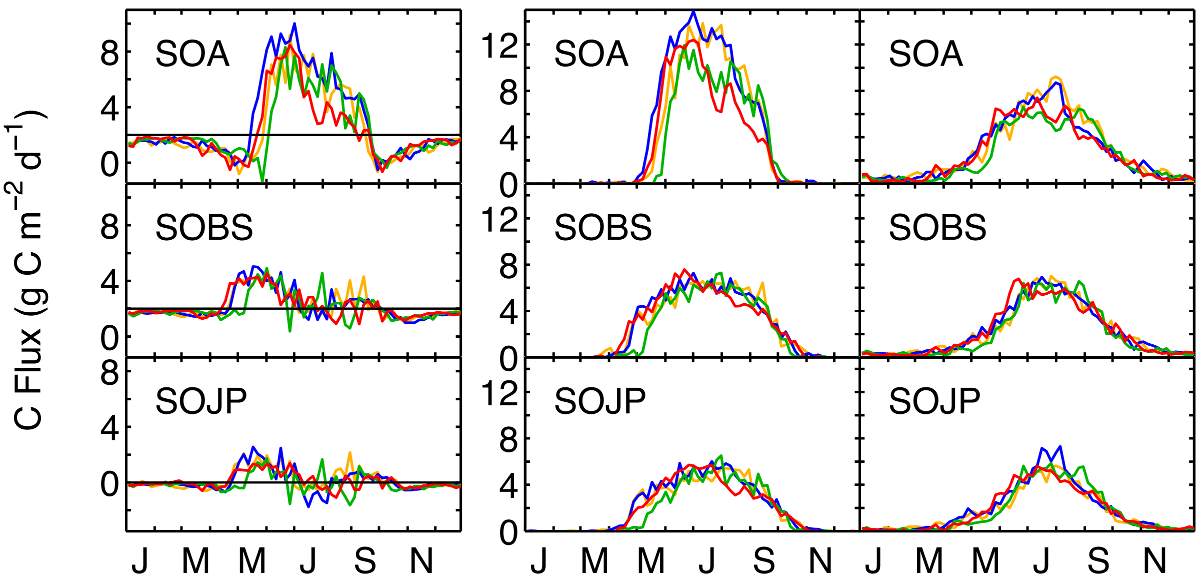

Figure 3: NEP (left column), GEP (middle column), R (right column) observed at the three sites in 2000 (orange), 2001 (blue), 2002 (green), and in 2003 (red) (5-day averages).

3.2 Drought Effects

Photosynthesis at SOA in 2001 remained at similar levels as in the previous year even after the onset of the drought in June (Figure 3). Despite little precipitation (Figure 2), the trees probably had access to soil water in deeper layers and thus were able to photosynthesise and transpire at normal rates. Ecosystem respiration at SOA, on the other hand, was reduced during the second half of the growing season 2001 (Figure 3). This reduction in R probably resulted from reduced heterotrophic respiration. Most of the heterotrophic respiration originates from the upper soil layers, which were already too dry to sustain it. The conifer ecosystems were not affected as much by the drought as SOA in 2001. Even more so, as expected for these ecosystems likely adapted to high water table and drought conditions, respectively, photosynthesis and respiration remained at normal rates (Figure 3).

In 2002, SOA still suffered the least rainfall of the three sites. Consequently, soil moisture at deeper depths decreased and the trees reduced their transpiration and photosynthesis (Figure 3). Not only heterotrophic, but also autotrophic respiration was reduced in 2002. The conifer sites again did not show a distinguishable reaction to the drought.

In 2003, the situation changed dramatically. Not only did SOA have to deal with another year of low precipitation, but precipitation at SOBS and SOJP dropped to a similarly low level (Figure 2). Thus 2003 was comparably dry at all three sites. At SOA, GEP was very low for most of the growing season. R was correspondingly low, especially between July and September 2003, but reached a higher total than in 2002 partly due to the early spring. The two conifer sites, on the other hand, showed only little reaction to the drought. Slight reductions in GEP and R occurred mainly in August 2003 (Figure 3).

3.3 Annual Carbon Uptake

In 2001, SOA sequestered 2.5 times more carbon than in 2000 (Figure 4). This extraordinarily high amount resulted from both the very high GEP due to the early start of photosynthesis and the reduced R due to the drought. GEP at SOBS and SOJP was in 2001 within the same range as in 2000 since the conifers did not benefit from an early spring. Also, R was not reduced in 2001 since the conifer sites were not as badly affected by the drought. Thus the net carbon uptake by the conifers remained the same (within the range of uncertainty).

In the following year, R was suppressed at all three sites as result of the short growing season. Nevertheless, NEP reached the lowest levels measured between 2000 and 2003, at all three sites, since annual GEP was also significantly reduced and thus outweighed the effect of reduced respiration. The main reason for the low annual GEP was probably not the drought but the very late start of photosynthesis. SOA and SOBS were still a sink of carbon in 2002 (SOBS however being close to neutral), while SOJP ended up as a carbon source.

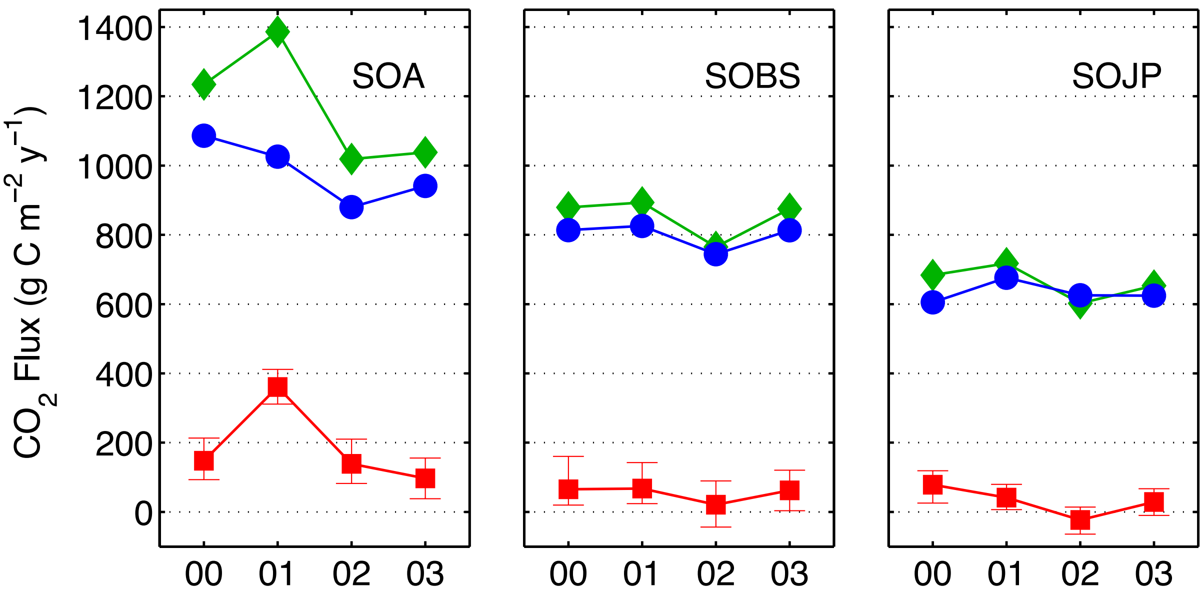

Figure 4: Annual NEP (red), GEP (green), and R (blue) for the three sites in 2000-2003.

Finally in 2003, at SOA, R was rather low and GEP was reduced by the drought. Thus the annual carbon sequestration at SOA remained low, at a level comparable to 2002. Even though the conifer sites suffered from a similar reduction in precipitation as SOA, they sequestered carbon at rates comparable to 2000 and 2001. Although SOA was impacted most by the drought, this stand clearly sequestered more carbon than SOBS and SOJP during the four analysed years.

4. SUMMARY AND CONCLUSIONS

Eddy correlation flux measurements of CO_2 and climate data obtained at three sites near Prince Albert National Park, Saskatchewan, were analysed. The time series included three years when the stands were affected by a drought. In addition, an early (warm) and a late (cold) spring occurred.

These forcings significantly affected the annual carbon budget of the forests. During the first drought year, low soil water content significantly decreased ecosystem respiration at the deciduous aspen site resulting in the second highest annual carbon sequestration in the nine years of flux monitoring at this site. In the second and third year of the drought, the trees appeared to suffer from water stress (reduced transpiration) and thus showed reduced photosynthesis. The conifer sites, on the other hand, showed only very limited reaction to the drought. The early spring resulted in higher GEP at the deciduous aspen site, but did not affect spring GEP at the conifer sites. The late spring, however, affected all three sites and caused SOJP to be a carbon source in 2002. When comparing the total carbon uptake at the three sites between 2000 and 2003, the deciduous stand clearly sequestered more carbon than the conifer stands, even though it was affected most by the drought.

ACKNOWLEDGEMENTS

This research was supported by NSERC, CFCAS, CCAF, SNF, and FCAR.

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