12.9   **COMPARISON OF NET ECOSYSTEM PRODUCTION AT
MATURE AND DISTURBED FOREST SITES, SASKATCHEWAN, CANADA 2001-02**

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1. Introduction

The Fluxnet international network of flux towers measures the exchange of carbon dioxide, water vapour and energy between the biosphere and atmosphere (Aubinet et al. 2000, Law et al. 2002, Wilson et al. 2003). In Canada, the network of flux towers in forested areas began during the BOREAS experiment where fluxes along a north-south climatic gradient of the boreal forest were measured (Sellers et al. 1997). After the termination of BOREAS in the mid-1990s, some of the flux towers continued operation at both the northern (Goulden et al. 1998) and southern study areas. The group of three main flux towers at the southern study area formed the basis of the Boreal Ecosystem Research and Monitoring Sites (BERMS). The southern old aspen (SOA) flux tower has run since BOREAS times, and the southern old black spruce (SOBS) and southern old jack pine (SOJP) flux towers were started again in 1999, providing valuable data on inter-annual variability of fluxes and the processes that drive surface-atmosphere exchange (Black et al. 2000, Griffis et al. 2003).

Despite the important information gained to date on mature forest functioning, especially related to carbon exchange, we have less knowledge of the boreal forest biome as a whole. This is because of the mosaic of boreal stand ages and types that are continuously being renewed through natural and human disturbances. Indeed, the carbon balance of the Canadian boreal forest is driven by these disturbances (Kurz and Apps 1999), and it is possible that water and energy balances that govern climate are also dictated by disturbance-generated surface conditions. Over the past few years, the BERMS program has begun to investigate spatial and temporal variability caused by forest disturbances. The main disturbances in the Canadian boreal forest are fire, insects, disease, windthrow and harvesting. Of these, fire is often regarded as the main stand-renewing agent, averaging more than 2 million ha

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burned annually over the past few decades, mostly as crown fires (Stocks et al. 2003). In addition, about 1 million ha are harvested annually in Canada, and this is a major stand-replacing mechanism in the managed part of the forest, mostly in the south. Although we recognize that the other disturbances are important for forest ecosystem function, we are presently concentrating on the effects of fire and harvesting. Hence, over the past few years, the BERMS program has added flux towers at sites burned in 1998, 1989 and 1977, and sites harvested in 1975, 1995 and 2001. This strategy provides data on various age classes reflecting the present landscape to help with scaling the boreal forest biome as a whole. It also provides temporal information as a chronosequence of events. In parallel, a fire chronosequence has also been established at the BOREAS northern study area (Litvak et al. 2003). The combination of these studies provides a significant improvement in our knowledge of boreal forest functioning, compared to the previous focus on mature stands alone. In 2002, the Fluxnet-Canada national network was formed, establishing sites that incorporate forest harvesting in British Columbia, Ontario, Quebec and New Brunswick as well as components of the BERMS program that were incorporated into the network. This will allow the carbon and water dynamics to be compared in different climates and forest types. This network contributes to the international Fluxnet network data sets (e.g., Falge et al. 2002, Gu and Baldocchi 2002, Law et al. 2002) by providing additional data for both mature and young northern forests.

Comparisons of disturbed and mature boreal forest sites during the growing season have shown that even very young stands (<20 years) old can be strong day-time carbon sinks (Amiro et al. 1999, Amiro et al. 2003) and even modest to strong daily sinks (Amiro 2001, Litvak et al. 2003). However, longer-term data are not yet available so the annual magnitude of the flux is unknown. We hypothesize that forests remain as an annual carbon source until crown closure, which is typically in the 20 to 30 year range after fire, depending on the area. The decomposition of fire-killed vegetation and coarse woody debris likely exceeds photosynthetic uptake during this period, but data are needed to

understand the magnitude of the net carbon flux. In contrast to fire, harvesting removes much of the coarse material so the respiration dynamics are expected to differ, perhaps causing the forest to become a carbon sink at an earlier age. Here, we report on the comparisons between mature and disturbed sites for 2001 and 2002. For this period, data are available for the three mature sites (SOA, SOBS, SOJP), sites burned in 1998 (F98) and 1989 (F89), and one site harvested in 1994 (HJP94).

2. Site Description

The basic attributes of each of the sites are summarized in Table 1. The normal successional development of forests in the BERMS area can be complicated. Although pure stands of sufficient fetch for tower-based flux measurements exist, they are rare and not typical. Instead, the forest is a mosaic with stand composition often changing on a scale of hundreds of meters. This also affects the successional trajectory following fire, since a mosaic regenerates depending on fire severity, site conditions and establishment method. There is often a competition among trembling aspen (*Populus tremuloides* Michx.), jack pine (*Pinus banksiana* Lamb.) and black spruce (*Picea mariana* (Mill.) BSP.), in areas where all three of these were present before fire. Aspen often regenerates through suckering from fire-killed parent trees, grows rapidly but is relatively short-lived. Both jack pine and black spruce regenerate from serotinous seeds, with jack pine growing more quickly, and black spruce eventually catching up and dominating if another fire does not occur. Hence, the mosaic at most fire sites reflects possible trajectories resulting in stands similar to SOA, SOBS or SOJP, but more likely being a combination of species. Hence, we use the data from the three mature stands to characterize the forest mosaic, without any one of these stands being necessarily representative of the landscape as a whole. Unlike fire, harvesting can result in an even-aged monospecific stand, and the HJP94 site represents the condition that would follow harvesting SOJP.

3. Methods

The basic method for eddy flux measurements used a sonic anemometer coupled with an infra-red gas analyser (IRGA). Both open and closed-path IRGAs were used, depending on the site. The closed-path systems had the IRGA mounted on top of the tower to allow for short (~4 m) lengths of tubing between the intake and the IRGA. Continuous high frequency (20 or 10 Hz) data were archived at most sites and post-processed to calculate the covariance at 30-min intervals. On-line cross-products only were saved at the two burned sites for covariance calculation. Coordinate rotations were done following the method of Tanner and Thurtell (1969), except at HJP94 where no rotation was done because the site was very flat. Energy and mass storage were included in the fluxes, although these terms become very small as daily totals. Net radiation (R_n) was measured using either four instruments (paired

Kipp and Zonen CM11, Delft, The Netherlands, and paired Eppley PIR, Newport, USA), or 4-component (Kipp and Zonen CNR1), or 2-way instruments (e.g., Middleton CN1, Melbourne, Australia or Kipp and Zonen NR-Lite). Down-welling photosynthetically-active radiation (PAR) was measured with quantum sensors (Licor Inc. LI190, Lincoln, NE, U.S.A.). Ground heat flux (G) measurements were made at all sites using heat flux plates with storage measured using soil thermocouples.

Quality control included removal of spikes in the high frequency data and periods of clearly bad half-hour data (e.g., caused by precipitation or malfunctions). Data below a specified u_* (friction velocity) threshold were also removed, with this threshold varying slightly among sites (Table 1). The remaining gaps were filled using two simple annual empirical relationships determined from measured data. One used the relationship between ecosystem respiration (R) and soil temperature at a shallow depth (usually 5 cm) and the other was between gross ecosystem productivity (GEP) and PAR above the stand. The 30-min fluxes were then integrated to get daily totals. NEE was calculated as the sum of the CO_2 covariance flux and the CO_2 storage below the flux measurement height. Net ecosystem productivity (NEP) was:

$$NEP = -NEE = GEP - R.$$

Our sign convention is that NEE is positive for carbon sources whereas NEP is positive for carbon sinks. Note that both GEP and R are given positive signs.

4. Results

Energy balance closure was calculated based on regression of the gap-filled daily totals of sensible and latent heat fluxes versus R_n-G. Closure ranged from 81 to 89% (Table 1). We believe that our best estimate of NEP needs to include losses due to underestimation of turbulent fluxes indicated by lack of energy balance closure. This is a well-known issue with most studies recognizing the need to include this factor (e.g., Twine et al. 2000, Wilson et al. 2002). Here we report daily values in Figure 1 without closure corrections, but all annual totals of NEP in Table 1 have been increased by the amount of closure underestimation.

Daily NEP

Weekly means of daily NEP are shown in Figure 1 for each of the six sites, with the graphs organized in chronological order, top to bottom, from oldest to youngest stand. Data are continuous for the three mature sites but there are data gaps at the younger sites. The HJP94 site began operation on March 24, 2001 and the F89 site began on July 6, 2001. Missing data at the F89 and F98 sites in the winter of 2001/02 were mostly caused by a power failure during cold temperatures. However, winter data were also excluded at these sites because of lack of confidence in the flux

measurements during winter using the open-path gas analysers.

The largest fluxes occurred at SOA. The strong annual cycle is clearly a function of the response of trembling aspen to phenology and weather with strong positive NEP when the leaves are out, particularly in early summer. Strong respiration occurred in spring and fall when soil temperatures were warm but there was little photosynthetic activity. Higher fluxes were experienced in 2001 than 2002. The SOBS and SOJP sites showed earlier positive NEP in spring than SOA because of the dominance of evergreen tree species. Both of these sites had days of negative NEP during summer, which was very rare at SOA. A period in late July 2001 is especially notable when SOBS, SOJP, F89 and F98 all showed negative NEP for several weeks. Winter NEP was less at SOJP than at the other two mature sites.

HJP94 showed a very small flux throughout the year, with more days being negative than positive. Winter respiration tended to be quite similar to that at SOJP. F89 showed a strong early spring NEP but became negative in late summer in both years. F98 showed a lower flux than F89 and spring NEP was negative. There were a fewer number of summer days when NEP was positive, but NEP was greater than at HJP94.

Annual Total NEP

Annual NEP, corrected for energy balance closure, was calculated at the mature sites using the continuous data (Table 1). NEP was greater in 2001 than 2002 at all mature sites by a factor of about three. SOA was the strongest carbon sink with SOJP being close to carbon neutral. For the younger sites, we filled the missing data periods using a combination of reasonable assumptions and statistical tests. At HJP94, winter NEP values were not significantly different between 2001 and 2002, where winter conditions were defined as the period from day 1 to 90 and day 305 to 365 (paired t-test, SYSTAT 1997, P=0.30, n=57 days). Hence, we used the 2002 data to fill the missing period in the early winter of 2001 to get annual NEP estimates. Annual NEP was quite similar between years, averaging -57 g C m^{-2} y^{-1}.

We found no significant difference for daily winter NEP between F98 and SOBS (Paired t-test, P=0.074, n=64 days) for days when we had data at both sites. We therefore filled winter respiration for F98 using SOBS data, although this does not imply that these two sites have similar carbon dynamics. F98 was a stronger source than HJP94 in both years. Although the winter gap filling makes these totals less certain, the site was still clearly a net source of carbon. If winter respiration at F98 was more similar to that at HJP94, then the annual totals would be -102 g C m^{-2} y^{-1} for 2001 and -55 g C m^{-2} y^{-1} for 2002, instead of -132 and -87, respectively.

We could not find an analogue for the F89 site based on statistical tests, largely because we only had about 20 days of F89 winter data that we trusted. F89 has a species mix that is a combination of those found at the three mature sites. Hence, we estimated the missing winter NEP for 2002 at F89 based on four scenarios, three of which use NEP from each of the mature sites, with the fourth being the mean NEP of the three mature sites. This gave total estimates for 2002 ranging from 18 to 106 g C m^{-2} y^{-1} with the mean being 68 g C m^{-2} y^{-1}. This site is clearly a net sink of a stronger magnitude than SOJP but less than SOA. This site started operating too late in 2001 to be able to estimate annual NEP for that year.

5. Discussion

It is difficult to construct flux experiments that will allow replications of treatments to compare forests of different ages. In the BERMS area, the vegetation mosaic dictates that there are few pure stands of sufficient fetch for eddy covariance measurements from towers. The three mature pure stands indicate the range of NEP for mature forests in this area. For these two years, we see mature forests ranging from relatively large carbon sinks of about 360 g C m^{-2} y^{-1} at SOA in 2001 to being a small source at SOJP in 2002. The high NEP at SOA in 2001 stands out as one of the highest years for carbon sequestration since annual measurements were made at this site (Black et al. 2000, Griffis et al. 2003). There is clearly a decrease in NEP at SOA, SOBS and SOJP in 2002 compared to 2001. At SOA, this is caused partially by a difference in spring temperature, with an early leaf emergence in 2001 and a late leaf emergence in 2002 (Barr et al. 2004). Data at SOA since 1994 show that warm springs (e.g., 1998) result in greater annual carbon sequestration (Black et al. 2000, Barr et al. 2004). In addition, there were dry conditions in both years with only about half the normal precipitation for this area (Griffis et al. 2003). This also translates to much lower ET at SOA in 2002 compared to 2001. SOBS and SOJP were also drier than normal, but did not experience the extreme drought conditions at SOA. In 2000, SOA, SOBS, and SOJP sequestered 122, 35 and 78 g C m^{2} y^{-1} (Griffis et al. 2003).

The regional drought conditions did not have much effect on interannual differences at HJP94 and F98, and both were annual carbon sources. Both F98 and F89 are much more dynamic than HJP94, with periods of greater positive and negative flux. This is partly caused by the greater deciduous and herbaceous cover at the post-fire sites, especially suckered aspen trees that have been growing rapidly. Hence, the differences here may mostly be caused by species differences, and not by differences in dynamics of heterotrophic respiration. This is uncertain without measurements of individual ecosystem components. A main difference between burned and harvested stands is that fire removes the fine materials and leaves the coarse woody material, whereas harvesting typically does the opposite. We would expect greater heterotrophic respiration following

harvesting in the early years until the finer material decomposes, whereas the burned-site heterotrophic respiration would likely not increase until killed trees have reached the ground, becoming moist and decaying. At the F98 site, most of the fire-killed trees are still standing or perched above ground, so very little of this wood is expected to be decaying and contributing to the respiration flux. Instead, NEP is probably dominated by photosynthesis of suckering aspen (up to 2 m tall), jack pine and black spruce seedlings, and ground vegetation. F89 has far less coarse woody material on the site because of some harvesting before the fire. The smaller values of NEP at HJP94 are a function of the young jack pine's ecophysiology since this site is dominated by this one species, with less surface vegetation than at the burned sites. The period of large negative NEP (net respiration) at F89 starting in mid-July 2001 followed a period of rain, where over 80 mm of rain fell within a four-week period. Although this period of negative NEP is also evident at SOBS, SOJP and F98, it is greatest at F89. Calculations indicate that this was mostly caused by enhanced daytime respiration, i.e., GEP was less affected. Although we do not have independent respiration measurements at this site, we hypothesize that the wetter conditions increased heterotrophic respiration by creating a moister environment for decomposition of coarse woody debris and leaf litter.

The issue of uncertainty is critical to estimates of NEP (Falge et al. 2001). Morgenstern et al. (2004) calculated annual random variability in NEP of the order of 4 g C $m^{-2}y^{-1}$, assuming a random error of about 20% for eddy covariance measurements throughout the year (Wesely and Hart 1985). They also found that biases were largely unaffected by interannual variability, making it possible to quantify differences among years. For multi-day to annual NEP, the greatest uncertainty is caused by choices made in data quality control and gap-filling. Using the BERMS mature site data for 2000, Griffis et al. (2003) estimated that NEP could range from 64 to 142, 18 to 53, and 61 to 91 g C $m^{-2}y^{-1}$ for SOA, SOBS and SOJP, respectively. Similarly, Schmid et al. (2003) estimated that gap-filling uncertainty is of the same magnitude as interannual variability at a mixed hardwood forest, where the forest was a net sink of the order of 80 to 170 g C $m^{-2}y^{-1}$. Large gaps can create estimates that differ by more than 100 g C $m^{-2}y^{-1}$ (Carrera et al. 2003), or turn estimates of net carbon sinks into sources (Saleska et al. 2003). For our data set, the annual uncertainty for the mature sites is assumed to be of the magnitude reported by Griffis et al. (2003), based on experiments in gap-filling by randomly removing up to 30% of the data. This indicates that SOA and SOBS were carbon sinks, but SOJP could be a small carbon source or sink in 2002.

Both HJP94 and F98 were clearly annual carbon sources. However F89 and F98 showed periods of both positive and negative NEP during the growing season (Figure 1). This clearly shows potential problems that could occur when collecting short-term data during field campaigns. For example, early season data at F89 in 2002 showed a sink whereas late season data showed a source. Previously, we published field campaign data from post-fire sites measured from towers and aircraft (Amiro et al. 2003). Although we recognized that winter respiration data were needed to estimate annual NEP, some of our conclusions about the potential source strength of early post-fire sites were likely in error. The current study indicates that the sites that are only a few years old are net carbon sources, consistent with carbon budget model predictions, at least in direction (Kurz and Apps 1999).

Uncertainty at F89 is much greater. We filled the missing winter data using data from each of the mature sites, as well as the mean of these for 2002. This gave annual NEP ranging from 18 g C $m^{-2}y^{-1}$ using respiration from SOA to 106 g C $m^{-2}y^{-1}$ using respiration from SOJP. Our mean of 68 g C $m^{-2}y^{-1}$ is thought to encompass the range of tree species at this site, although a straight average is a crude guess. Irrespective of this uncertainty, F89 is estimated to be a carbon sink in 2002 of perhaps half the magnitude of SOA, but greater than SOBS or SOJP. The dynamics also depends on environmental conditions, since the drought situation at SOA clearly influences NEP and this drought is not evenly distributed across the BERMS area.

Over the last few years, several research groups have been measuring carbon and energy fluxes over boreal forests that have been recently disturbed by fire or harvesting. Most of these studies report data for field campaigns or for the full growing season. Very young forests are carbon sources with slightly older successional forests being carbon sinks (Meroni et al. 2002, Amiro et al. 2003, Litvak et al. 2003,) or close to carbon neutral (Schulze et al. 1999) during the growing season. These studies have been important to help us understand the functioning of younger forests, and how they contribute to the carbon balance in summer. However, it is clear that young forests can be either sources or sinks depending on the period during the growing season (Figure 1) and we urge caution when interpreting the limited data sets.

6. Conclusions

The expansion of flux measurement sites to include forests of various ages is key to estimating net biome production in the boreal forest. In Canada alone, an average of two to three million ha burn annually, with another one million ha harvested. The resulting mosaic of stand ages has features that are just starting to be characterized by the flux measurement community, especially on annual scales. We need to expand measurements to reduce the uncertainty in carbon and energy flux estimates, and to allow for scaling up to the ecoregion or biome level using models. The carbon budget model of the Canadian forest sector clearly demonstrates the importance of fire, insect and harvesting disturbances on the overall carbon balance

(Kurz and Apps 1999). However, confidence in these model estimates will be greatly strengthened by direct measurements over several years, incorporating post-disturbance effects.

Projections of future climate suggest that fire will become even more important with possibly a doubling of area burned in Canada by the end of this century (Flannigan et al. 2004). Other boreal areas, such as Siberia, may also see similar increases in fire. This, coupled with the potential for more insect infestations (Volney and Fleming 2000), means that the proportion of younger successional forests could increase. Changes to large expanses of boreal forest would alter energy balance partitioning (e.g., Chambers and Chapin 2003) and albedo (Betts 2000, Chapin et al. 2000), which may alter regional and global climates. In addition, more disturbance could increase seasonal amplitudes of atmospheric CO_2 because successional vegetation has higher summer and winter fluxes (Zimov et al. 2000).

Acknowledgements

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Table 1: Site characteristics. Canopy characteristics for SOA, SOBS and SOJP are from Gower et al. (1997). The NEP annual totals include energy balance closure (positive values are gains by the forest ecosystem).

	SOA	SOBS	SOJP	HJP94	F98	F89
Site description reference	Chen et al. 1999	Jarvis et al. 1977	Baldocchi et al. 1997	Iwashita et al. 2004	Amiro et al. 2003	Amiro et al. 2003
Year of origin	1919	1879	1929	1994	1998	1989
Lat./Long.	53.629N 106.200W	53.987N 105.117W	53.916N 104.69W	53.908N 104.656W	53.917N 106.078W	54.254N 105.877W
Canopy height (m)	21	7	13	2	18 (dead) 1 (live)	4
LAI	5.8	4.2	2.5	0.6	1.0	
Tree stem density	980	5900	1190	8625 includes young saplings	1100 dead	4000
Dominant tree d.b.h. (cm)	21	7	13	1	15 dead	4
Dominant tree Species	aspen	black spruce	jack pine	jack pine	aspen, jack pine, black spruce	aspen/poplar, jack pine, black spruce
Flux height (m)	33	25	28	5	10, 20	6, 10
Anemometer model	R3	R3	CSAT3	Kaijo SAT-550	CSAT3	CSAT3
IRGA	LI6262	LI6262	LI6262	LI6262	LI6262 /LI7500	LI7500
Energy balance closure fraction (r^2 value)	0.87 (0.95)	0.89 (0.97)	0.85 (0.89)	0.81 (0.92)	0.87 (0.73)	0.88 (0.91)
u_* threshold (m s^{-1})	0.35	0.35	0.3	0.1	0.25	0.25
2001 NEP (g C m^{-2} y^{-1})	361	68	41	-55	-132	
2002 NEP (g C m^{-2} y^{-1})	139	21	-23	-59	-87	68

Figure 1: Daily NEP (g carbon m^{-2} d^{-1}) in 2001 and 2002 as weekly means. Energy balance corrections are not included but would increase the fluxes by amounts shown in Table 1.