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## 1. INTRODUCTION

Mature boreal forests are very important sinks for atmospheric carbon dioxide (CO<sub>2</sub>) the major greenhouse gas (GHG) implicated in global warming. However, following disturbance (e.g. fire, harvesting, wind-throw and insects), boreal forests may become a CO<sub>2</sub> source for several years. For example, following clear-cut harvesting a boreal jack pine forest in central Canada changed from a strong carbon (C) source at 2 years to a weak C source at 10 years, a significant C sink at 30 years and a weak or neutral C sink at 90 years (Zha et al. 2008, in review). In recent decades, the Canadian boreal forest has likely changed from a C sink to a C source mainly because of natural disturbance i.e., fire and insects (Kurz and Apps 1999, Kurz et al. 2008).

Fire and harvesting are recognised as major forest renewal processes in many forests, especially the Canadian boreal. On average 2-3 million ha of forest are burned each year, while 1 million ha are harvested (Kurz and Apps, 1999). Both fire and harvesting impact the age and species composition and alter the surface characteristics of the forest, thus impacting the C, water and energy dynamics of the forest. The main difference between fire and harvesting is that fire removes the fine organic material, leaving the woody material, while harvesting does the opposite (Amiro et al., 2006; Coursolle et al., 2006).

Many studies have evaluated C dynamics of boreal forests following fire or harvest, but only a few have compared directly the two forest renewal mechanisms; although Schulze et al. (1999) have summarised a range of forests from Europe, Asia and North America. The few studies where the two processes have been compared have been short-term and have used a limited number of sites. For example, Amiro et al. (2006) compared C, water and energy budgets of two young post-fire boreal forests and one harvested site for two years.

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In another short-term study, Coursolle et al. (2006) evaluated late-summer (August) C fluxes from Canadian boreal forests and found that young post-fire sites had higher net ecosystem productivity (NEP) compared to young post-harvest sites and attributed this to the presence of both coniferous and deciduous species on the fire sites.

The challenges to comparing the impact of the renewal processes of fire and harvesting are related to establishing treatments on sites that have similar climates, soil conditions, and tree species. This is confounded by the requirement to establish experimental treatments of sufficient scale (>100 ha) to allow for eddy covariance (EC) measurements of whole ecosystem exchange, and by the availability of historical conditions and management practices that include both fire and harvesting. The major objective of this study was to compare and contrast carbon dynamics following fire and harvesting using data collected in 2005 from several Canadian boreal forest sites at different stages of development. The sites are part of the Boreal Ecosystem Research and Monitoring Sites (BERMS) project, where flux towers have been operating for over a decade following the BOREAS experiment (Sellers et al. 1997). The BERMS experiments were set up to allow multi-year comparisons of fire and harvesting effects on carbon fluxes.

## 2. METHODS

### 2.1 Experimental Location and Site Description

The study sites are located in central Saskatchewan (about 54°N, 106°W) (Table 1), Canada and are within 100 km of each other with relatively similar climates. Net ecosystem CO<sub>2</sub> exchange (NEE) data collected in 2005 from three post-fire sites (F77: burned in 1977, F89: burned in 1989, F98: burned in 1998), three post-harvest sites (HJP75: harvested in 1975, HJP94: harvested in 1994, HJP02: harvested in 2002) and one mature site (OJP: last burned in 1929) were utilised in this study. The harvested sites and OJP are dominated by relatively pure stands of jack pine (*Pinus banksiana* Lamb). The fire sites, however,

Table 1. Site location and characteristics

	F77	F89	F98	OJP	HJP75	HJP94	HJP02
Year of origin	1977	1989	1998	1929	1975	1994	2002
Latitude	54.49N	54.25N	53.92N	53.92N	53.88N	53.91N	53.95N
Longitude	105.82W	105.88W	106.08W	104.69W	104.65W	104.66W	104.65W
Elevation (m)	563	540	548	579	534	580	580
Soil texture	Sandy loam	Sandy loam	Sandy loam	Sandy	Sandy	Sandy	Sandy
Canopy height (m)	6	4	18 dead 1 live	17.7	7.6	1.7	--
LAI	2.8	3	1.3	2	3.1	0.8	--
Dominant over-storey tree species	Jack pine	Jack pine, Trembling aspen	Jack pine, Black spruce	Jack pine	Jack pine	Jack pine	Jack pine
Dominant under-storey tree species	Black spruce	Black spruce	Jack pine, Trembling aspen, Black spruce	none	none	none	none
Sonic anemometer model	CSAT3	CSAT3	CSAT3	CSAT3	Gill R3-50	SAT-550	CSAT3
IRGA	LI-7500	LI-7500	LI-7500	LI-6262	LI-7000	LI-6262	LI-6262
Flux height (m)	12	6, 10	10, 20	29	16	6	5
$u$ threshold ( $m s^{-1}$ )	0.25	0.25	0.25	0.35	0.35	0.1	0.1

Adapted from: Amiro et al. (2006), Coursolle et al. (2006) and Zha et al. (2008)

have a mixture of jack pine, black spruce (*Picea mariana*), and trembling aspen (*Populus tremuloides*), but were dominated by jack pine prior to the fire (Table 1). In addition, the soils at the harvested sites are sandier than at the fire sites, even though they are all classified as brunisols. It is extremely difficult to match exactly the site characteristics among treatments, even in the same geographical area.

## 2.2 CO<sub>2</sub> Flux and Meteorological Measurements

At all sites the eddy covariance (EC) technique was used to measure turbulent fluxes of carbon dioxide (CO<sub>2</sub>), latent heat ( $\lambda E$ ) and sensible heat (H) continuously throughout the year. At the fire sites, the instrumentation consisted of sonic anemometers (model CSAT3 Campbell Scientific., Logan, UT, U.S.A. and Edmonton, Canada) and open-path infrared gas analysers (IRGA) (model LI-7500 LICOR Inc, Lincoln, NE, USA) mounted within 30 cm of the sonic array. At the harvested and OJP sites, the instrumentation consisted of a sonic anemometer (model R3-50, Gill Instruments Ltd, Lymington, UK, at HJP75; model SAT-550, Kaijo Co., Tokyo, Japan, at HJP94; model CSAT3, Campbell Scientific Inc., at HJP02 and OJP), and a closed-path infrared gas analyzer (model LI-6262, LI-COR Inc, Lincoln, NE, USA, at HJP02, HJP94, and OJP; model LI-7000, LI-COR Inc., at HJP75) (Table 1). The IRGAs were housed in temperature-controlled housings allowing year-round sampling. Air samples were drawn into the IRGAs at 10 L min<sup>-1</sup> using 3-4 m long heated sampling tubes. The IRGAs were calibrated frequently using gases of known CO<sub>2</sub> concentration. The instruments at each site were mounted above the canopy on scaffolding or triangular towers. Net ecosystem

exchange (NEE) was calculated from the 30-min flux and storage below the flux measurement height. Net ecosystem production (NEP) was calculated as negative NEE (-NEE). Positive NEP corresponds to C gained by the ecosystem whereas negative NEP indicates C lost to the atmosphere.

Supporting meteorological measurements recorded at each site included air and soil temperature, soil heat flux (G), volumetric soil water content ( $\theta_v$ ) and photosynthetically active radiation (PAR). Air temperature from several heights at each site was measured using HMP45C temperature/humidity probes (Campbell Scientific Inc.). Soil temperature at various depths was measured using either chromal-constantan or copper-constantan thermocouples, while G was measured using heat flux plates (Thornthwaite Model 610, Pitts Grove, NJ, USA). At the OJP site, the soil heat flux was measured at two locations using Middleton plates (model CN3, Middleton Solar, Yarraville, Victoria, Australia).

Volumetric soil water content ( $\theta_v$ ) at various depths was measured using time domain reflectometers model CS615 (Campbell Scientific Inc.). PAR was recorded using either ML-020P (Eko, Co., Ltd., Tokyo, Japan) or LI-190 (LI-COR Inc, Lincoln, NE, USA) quantum sensors. More information on the sites and measurements is provided by Amiro et al. (2006) and Zha et al. (2008).

## 2.3 Data processing and gap-filling procedures

Data quality control included removal of spikes caused by instruments malfunction and other causes.

Night-time flux data below a site-specific friction velocity ( $u_*$ ) threshold were also removed (Table 1). Missing data were gap-filled using standard methods developed by the Fluxnet-Canada Research Network (Barr et al., 2004, Amiro et al. 2006). The methods used the relationship between ecosystem respiration ( $R_e$ ) and soil temperature at a 5 cm depth to fill missing respiration data and photosynthetic uptake was filled through a relationship between gross ecosystem productivity (GEP) and above-canopy incoming PAR. Gaps of two hours or less (i.e., four data points) were filled through linear interpolation. Measurements at the F77, F89 and F98 sites were made with open-path IRGAs. Our experience has been that these instruments do not give reliable measurements during cold temperatures, with some of the issues likely caused by instrument heating (Amiro et al. 2006; Grelle and Burba 2007). Hence, we excluded flux measurements when the air temperature  $< 0^\circ\text{C}$ , and filled these winter gaps using site-specific regressions between soil temperature at the 2-cm depth and night-time NEE for an air temperature dataset between 0 and  $10^\circ\text{C}$  (Sass 2007).

#### 2.4 Environmental controls on $\text{CO}_2$ exchange

Regression analyses using non-gap-filled data were performed to relate ecosystem respiration ( $R_e$ ) to soil temperature ( $T_s$ ) at the 2 cm depth, and to relate gross ecosystem (GEP) to photosynthetically active radiation (PAR). We used an exponential equation to relate  $R_e$  to  $T_s$  as follows:

$$R_e = A \cdot \exp(B \cdot T_s) \quad (1)$$

where  $R_e$  is ecosystem respiration, A and B are fitted parameters and T is the soil temperature at the 2-cm depth. The relative change in respiration rate for a  $10^\circ\text{C}$  change in soil temperature (i.e. temperature sensitivity coefficient;  $Q_{10} = \exp(B \cdot 10)$ ) and the respiration rate at a reference soil temperature of  $10^\circ\text{C}$  ( $R_{10} = A \cdot Q_{10}$ ) were calculated using the derived parameters. Only night-time data recorded when the friction velocity ( $u_*$ ) was greater than a site-specific threshold (Table 1) and soil temperature was above zero for the period 1 May to 30 September were used. The data were bin-averaged with bin widths of  $2^\circ\text{C}$ . Meanwhile, to relate GEP to PAR we used non gap-filled bin-averaged (bin widths  $50 \mu\text{mol m}^{-2} \text{s}^{-1}$ ) day time data ( $\text{PAR} > 5 \mu\text{mol m}^{-2} \text{s}^{-1}$ ) and  $u_* >$  a site-specific threshold (Table 1) for the period 1 June to 31 August using the following equation:

$$\text{GEP} = \frac{A \cdot \text{PAR}}{B + \text{PAR}} \quad (2)$$

where GEP is gross ecosystem production, A and B are fitted parameters and PAR is the photosynthetically active radiation.

We calculated average water use efficiency (WUE) at each site as the ratio of total GEP to total

evapotranspiration (ET) using data for the period 1 June to 31 August. We selected GEP instead of NEE for the WUE calculation to avoid issues with  $R_e$  that would arise from decomposition of coarse woody debris and other heterotrophic processes in the younger sites. Data manipulation and statistical analyses were done using Matlab (Version 7.3.0, The MathWorks, Natick, MA, USA).

### 3. RESULTS AND DISCUSSION

#### 3.1 Gross Ecosystem Productivity (GEP)

At all sites GEP increased in spring reaching a peak during mid-summer and thereafter declined in response to changes in air temperature and solar radiation (Fig. 1a). Generally, the fire sites had higher GEP compared to the harvested sites. The fire site F89 recorded the highest GEP (maximum  $\sim 10 \text{ g C m}^{-2} \text{ d}^{-1}$ ) followed by F77 (maximum  $\sim 7 \text{ g C m}^{-2} \text{ d}^{-1}$ ) while HJP02 recorded the lowest (maximum  $\sim 1 \text{ g C m}^{-2} \text{ d}^{-1}$ ). The OJP site had relatively similar GEP to the much younger harvested sites (HJP75 and HJP94) and the youngest fire site F98, with a maximum GEP of approximately  $4 \text{ g C m}^{-2} \text{ d}^{-1}$ . The generally higher GEP at the fire sites compared to the harvested sites may be attributed to the presence of both coniferous and deciduous species on the fire sites resulting in higher photosynthesis at the fire sites during the summer. The presence of both coniferous and deciduous species impacts both the maximum flux and the period of GEP, with deciduous forests having a shorter growing season. Another factor that may have contributed to the higher GEP at the burned sites, particularly at F77 and F89 was the greater soil water content at these sites compared to the harvested sites (data not shown). Higher soil water content (i.e., reduced drought stress) tends to enhance photosynthesis. When comparing  $\text{CO}_2$  exchange for several Fluxnet-Canada research network sites, Coursolle et al. (2006) also observed that F89 and F77 had relatively high values of maximum GEP compared to many other forest ecosystems, even those older.

#### 3.2 Ecosystem Respiration ( $R_e$ )

Ecosystem respiration ( $R_e$ ) followed a similar trend as GEP; it increased during spring reaching a peak in late summer and then declined (Fig. 1b). However,  $R_e$  reached the maximum later in the season ( $\sim 5$  weeks later) compared to GEP, indicating a lag in  $R_e$ . This lag in  $R_e$  is likely caused by low soil temperatures during spring and the fact that the forest may initially replenish carbohydrate reserves prior to resumption of growth (Bergeron et al. 2007; Dunn et al. 2007; Goulden et al. 1997), plus higher soil temperatures in late summer that likely enhance heterotrophic respiration.  $R_e$  fluxes were generally higher for the fire sites than the harvested sites. The fire sites F77 and F89 recorded the greatest  $R_e$  fluxes (maximum  $\sim 8 \text{ g C}$

$\text{m}^2 \text{d}^{-1}$ ), while HJP02 recorded the lowest (maximum  $\sim 3 \text{ g C m}^{-2} \text{d}^{-1}$ ). The other sites OJP, HJP75, HJP94 and F98 recorded relatively similar  $R_e$  fluxes (maximum  $\sim 4 \text{ g C m}^{-2} \text{d}^{-1}$ ). The higher  $R_e$  fluxes from F77 and F89 may be caused by decomposing coarse woody debris. These two sites also have greater soil surface respiration than F98, which is due in part to higher root respiration (Singh et al. 2008). Soil surface respiration contributes 48-71%  $\text{CO}_2$  to  $R_e$  in Canadian boreal forests (Lavigne et al. 1997), but can be as high as 88% (Khomik et al 2006). Additionally, we suspect that the more vigorous successional vegetation at these young fire sites also has greater  $R_e$  than the less diverse vegetation at the recently harvested sites.

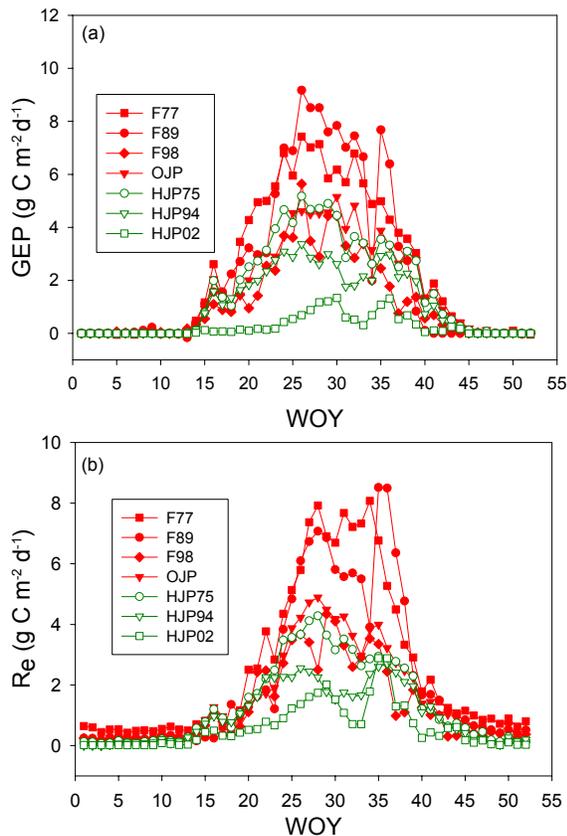


Fig. 1. Mean weekly (a) gross ecosystem productivity (GEP) and (b) ecosystem respiration ( $R_e$ ) for three post-fire sites (F77, F89, and F98), three post-harvest sites (HJP75, HJP94, and HJP02) and one mature site (OJP).

### 3.3 Cumulative Net Ecosystem Productivity (NEP)

Cumulative NEP shows that HJP02 was a C source throughout the year; F89 became a C sink by day of the year (DOY)  $\sim 130$ , while HJP75 and OJP became C sinks by DOY  $\sim 140$  and remained so until the end of the year (Fig. 2). Meanwhile, F77 became a C sink by DOY 140 and then became a C source by DOY

240 until the end of the year. HJP94 and F98 were relatively C neutral by DOY 130 and 180, respectively, and remained so until DOY  $\sim 280$  when they became moderate C sources at almost similar magnitudes. F89 reached a maximum of  $\sim 210 \text{ g C m}^{-2}$  by late summer and dramatically declined to  $\sim 50 \text{ g C m}^{-2}$  by the end of the year. Similarly, F77 reached a maximum of about  $75 \text{ g C m}^{-2}$  by mid summer and then collapsed to about  $-80 \text{ g C m}^{-2}$  by the end of the year. The dramatic decline in NEP for both F77 and F89 was likely caused by higher  $R_e$  than GEP during the summer at these sites. The high  $R_e$  at these sites is most probably a result of decaying coarse woody material.

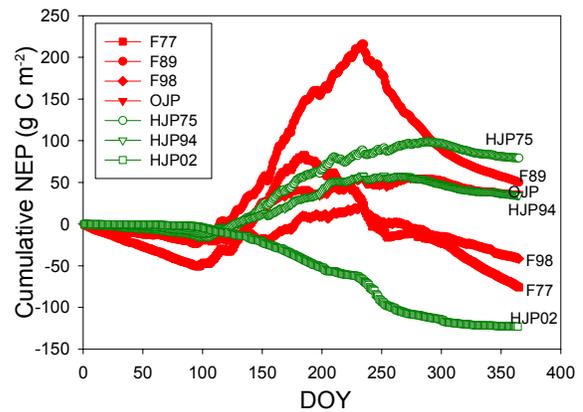


Fig. 2. Cumulative net ecosystem productivity (NEP) for three post-fire sites (F77, F89, and F98), three post-harvest sites (HJP75, HJP94, and HJP02) and one mature site (OJP).

### 3.4 Annual Carbon (C) Balance

The age of the forest stand influences the annual C balance, particularly following harvest. HJP02 was the strongest C source of any of the sites, losing  $\sim 125 \text{ g C m}^{-2} \text{y}^{-1}$  (Fig. 3). The  $R_e/\text{GEP}$  ratio for this site was 2.24, indicating that overall C dynamics at this site was dominated by  $R_e$  (Table 2). Zha et al. (2008) recorded an annual average  $R_e/\text{GEP}$  ratio of 2.52 for this site. In European forests,  $R_e$  is the main determinant of net ecosystem C exchange (Valentini et al. 2000). Similar to HJP02, HJP94 was a moderate C source losing  $\sim 55 \text{ g C m}^{-2} \text{y}^{-1}$  whereas HJP75 was the largest C sink of any of the sites, accumulating  $\sim 80 \text{ g C m}^{-2}$ . The OJP site was a small sink totalling about  $35 \text{ g C m}^{-2}$  with a  $R_e/\text{GEP}$  ratio of 0.94. Among the three youngest fire sites, stand age seemed to have no major role. Both F77 and F98 were C sources of about  $-80$  and  $-45 \text{ g C m}^{-2}$ , respectively, with a similar ratio  $R_e/\text{GEP}$  of 1.09. Conversely, F89 was the second largest C sink, accumulating about  $55 \text{ g C m}^{-2}$ , with a  $R_e/\text{GEP}$  ratio of 0.94. The higher source strength at F77 was somewhat surprising considering that F89 and HJP75 (closer in age) were moderate C sinks. This may be in part caused by actively decaying woody material contributing to

higher  $R_e$  compared to the other sites, particularly the harvested sites. This may indicate that C dynamics following fire go through four phases compared to three phases for harvested sites: i.e., soon after fire, burned sites become C sinks, then become C sinks, and then become C sources again when the dead woody material starts decaying and thereafter become C sinks or neutral. In contrast, harvested sites are C sources soon after harvest; C sinks at intermediate age and C neutral at maturity. However, this hypothesised pattern is still uncertain because of only three points in each chronosequence at ages <50 years. These results emphasise the need for continued measurements at these fire sites.

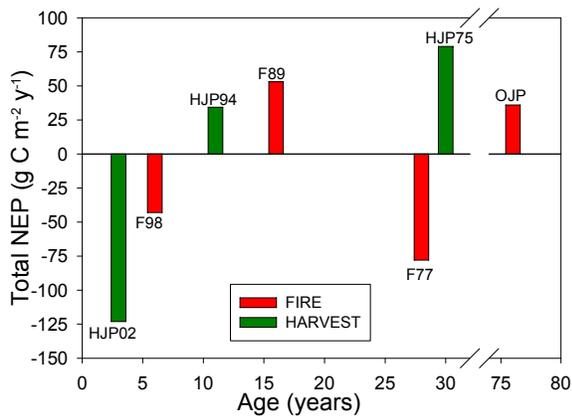


Fig. 3. Total net ecosystem productivity (NEP) for three post-fire sites (F77, F89, and F98), three post-harvest sites (HJP75, HJP94, and HJP02) and one mature site (OJP).

Table 2. Ratio of ecosystem respiration to gross ecosystem production ( $R_e/GEP$ ), temperature coefficient of ecosystem respiration ( $Q_{10}$ ), ecosystem respiration at a reference temperature of 10 °C ( $R_{10}$ ), June to August evapotranspiration (ET) and water use efficiency (WUE) for three post-fire sites (F77, F89, F98), three post-harvest sites (HJP75, HJP94, HJP02) and one mature site (OJP).

Site	$R_e/GEP$ ratio	$Q_{10}$ $\mu\text{ mol m}^{-2}\text{ s}^{-1}$	$R_{10}$ $\mu\text{ mol m}^{-2}\text{ s}^{-1}$	ET (mm)	WUE (g C kg <sup>-1</sup> H <sub>2</sub> O)
F77	1.09	4.27	5.79	281	2.00
F89	0.94	5.19	4.53	313	2.02
F98	1.09	2.92	2.30	245	1.30
OJP	0.94	3.59	2.35	156	2.39
HJP75	0.87	3.53	1.91	177	2.08
HJP94	1.06	2.50	1.60	143	1.65
HJP02	2.24	4.17	0.80	117	0.57

### 3.5 Water Use Efficiency

Cumulative ET for June to August was higher for the fire sites relative to the harvested sites (Table 2). The youngest harvested site, HJP02, had the lowest ET

(117 mm), while F89 had the highest (313 mm). Total annual ET at F89 also tends to be higher than nearby sites (Amiro et al. 2006). Jarvis et al. (1997) recorded total ET of 237 mm over 120 days (growing season) for a boreal black spruce in Saskatchewan. The higher ET at the fire sites compared to the harvested sites was likely, in part, a result the presence of both deciduous and coniferous trees, coupled with higher soil water content at the fire sites.

Regardless of the method of disturbance, recently disturbed sites tend to use water less efficiently, likely because of greater relative surface evaporation compared to whole ecosystem evapotranspiration, without carbon uptake through leaves. Water use efficiency (WUE) was lowest for HJP02 at ~0.6 g C kg<sup>-1</sup> water, followed by F98 at ~1.3 g C kg<sup>-1</sup> water and then HJP94 at ~1.7 g C kg<sup>-1</sup> water (Table 2). All the other sites had relatively similar WUE values ranging from 2 to 2.4 g C kg<sup>-1</sup> water, with the highest value being for OJP. Coursolle et al. (2006) recorded WUE values for HJP02, F89, F77, F98, HJP94 and OJP at 0.05, 3.3, 2.5, 1.1, 1.6 and 1.5 g C kg<sup>-1</sup> water, respectively, which are within our values for the same sites. Meanwhile, McCaughey et al. (2006) estimated an average daily WUE of 2 to 2.5 g C kg<sup>-1</sup> water for a boreal mixed-wood forest in Ontario.

### 3.6 Environmental controls of $R_e$ and GEP

#### 3.6.1 Relationship between $R_e$ and $T_s$

At all the sites,  $R_e$  increased exponentially with increasing soil temperature ( $T_s$ ) at the 2-cm depth (Fig. 4). The F89 site had the greatest temperature response with a  $Q_{10}$  value >5; the other sites had  $Q_{10}$  values <5 (Table 2). In the absence of water stress, larger  $Q_{10}$  values indicate greater temperature sensitivity (Khomik et al. 2006). We also calculated mean respiration rates scaled to a reference temperature of 10 °C ( $R_{10}$ ) for each site to remove the influence of differential soil temperatures among sites. The fire sites F77 and F89 had the greatest  $R_{10}$  values (5.8 and 4.5  $\mu\text{ mol m}^{-2}\text{ s}^{-1}$ , respectively), whereas HJP02 had the lowest (0.8  $\mu\text{ mol m}^{-2}\text{ s}^{-1}$ ) (Table 2). The  $Q_{10}$  and  $R_{10}$  values reported in the current study are within those reported by other researchers for boreal forest ecosystems (Bergeron et al. 2007; Giasson et al. 2006; Humphreys et al. 2005, 2006). At all sites, the relationships between  $R_e$  and  $T_s$  were highly significant ( $p < 0.001$ ) with  $R^2$  values ranging from 0.83 to 0.98, depending on the site. McCaughey et al. (2006) reported that  $T_s$  at 2-cm depth accounted for 93% of the variation in  $R_e$  in a boreal mixed-wood forest, while Barr et al. (2007) found that  $T_s$  at 2-cm depth accounted for 69% of the variation in  $R_e$  in a boreal aspen forest.

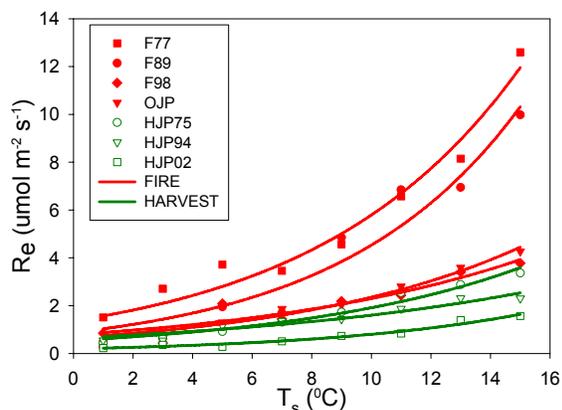


Fig. 4. Relationship between ecosystem respiration ( $R_e$ ) and soil temperature ( $T_s$ ) at 2-cm depth for three post-fire sites (F77, F89, and F98), three post-harvest sites (HJP75, HJP94, and HJP02) and one mature site (OJP) in 2005.

### 3.6.2 Relationship between GEP and PAR

At all sites GEP increased with increasing PAR, with PAR accounting for 77% to 96% of variation in GEP depending on the site (Fig. 5). Humphreys et al. (2006) reported that PAR accounted for 56% to 78% of the variation in GEP in coastal Douglas-fir stands. The response of GEP to PAR was highest at F89 followed by F77 and lowest at HJP02 followed by HJP94. F98, HJP75 and OJP had similar light responses. F89, F77 and OJP showed a decline in GEP at  $PAR \geq 1400 \mu\text{mol m}^{-2} \text{s}^{-1}$ , probably a result of stomatal closure. A decline in GEP at  $PAR > 1000 \mu\text{mol m}^{-2} \text{s}^{-1}$  has been previously reported for other forest and tundra sites (Suyker and Verma 1997, Humphreys et al. 2005, Lafleur and Humphreys 2008).

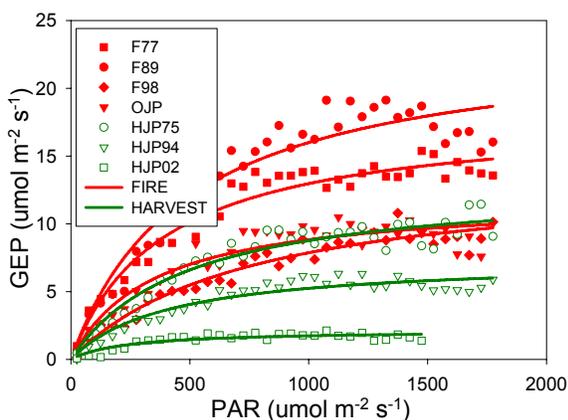


Fig. 5. Relationship between gross ecosystem productivity (GEP) and photosynthetically active radiation (PAR) for three post-fire sites (F77, F89, and F98), three post-harvest sites (HJP75, HJP94, and HJP02) and one mature site (OJP) in 2005.

## 4. CONCLUSIONS

Generally, the fire sites had higher GEP,  $R_e$  and ET than the harvested sites, which we believe is largely a result of the greater species diversity at the fire sites coupled with higher soil water content. NEP was generally negative for the younger sites, indicating that, regardless of disturbance mechanism, recently disturbed sites are C sources. The F77 site was a significant C source because of the higher  $R_e$  compared to GEP in the summer time, most likely a result of to decaying woody material at this site enhancing  $R_e$ . Water use efficiency was lowest for the youngest sites (HJP02, HJP94 and F98), most likely because of greater relative surface evaporation from these sites. At all sites, there was a positive exponential relationship between  $R_e$  and  $T_s$  at the 2-cm depth, with F89 and F77 having the strongest responses. Similarly, GEP increased with PAR at all sites with F89 and F77 having the greatest responses. The significant loss of ecosystem C by the F77 site, three decades after disturbance, suggest a more dynamic trend that may be different than that of harvested sites. Thus, there is a need for better characterisation of forest development following disturbance, particularly after fire, which we have not yet fully captured.

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